

# THE PROBLEM OF *HIPPARCOS* DISTANCES TO OPEN CLUSTERS. I. CONSTRAINTS FROM MULTICOLOR MAIN-SEQUENCE FITTING<sup>1</sup>

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## ABSTRACT

Parallax data from the *Hipparcos* mission allow the direct distance to open clusters to be compared with the distance inferred from main-sequence (MS) fitting. There are surprising differences between the two distance measurements, indicating either the need for changes in the cluster compositions or reddening, underlying problems with the technique of MS fitting, or systematic errors in the *Hipparcos* parallaxes at the 1 mas level. We examine the different possibilities, focusing on MS fitting in both metallicity-sensitive  $B-V$  and metallicity-insensitive  $V-I$  for five well-studied systems (the Hyades, Pleiades,  $\alpha$  Per, Praesepe, and Coma Ber). The *Hipparcos* distances to the Hyades and  $\alpha$  Per are within 1  $\sigma$  of the MS-fitting distance in  $B-V$  and  $V-I$ , while the *Hipparcos* distances to Coma Ber and the Pleiades are in disagreement with the MS-fitting distance at more than the 3  $\sigma$  level. There are two *Hipparcos* measurements of the distance to Praesepe; one is in good agreement with the MS-fitting distance and the other disagrees at the 2  $\sigma$  level. The distance estimates from the different colors are in conflict with one another for Coma but in agreement for the Pleiades. Changes in the relative cluster metal abundances, age related effects, helium, and reddening are shown to be unlikely to explain the puzzling behavior of the Pleiades. We present evidence for spatially dependent systematic errors at the 1 mas level in the parallaxes of Pleiades stars. The implications of this result are discussed.

*Subject headings:* Hertzsprung-Russell diagram — open clusters and associations: general — stars: abundances — stars: distances — stars: evolution

## 1. THE PROBLEM

Main-sequence fitting is a basic tool used in the study of star clusters; the principle behind it is also used to estimate distances to field main-sequence (MS) stars. The *Hipparcos* mission (European Space Agency 1997) has provided parallaxes for a number of open cluster stars, which permits a direct determination of the distances to the open clusters that can be compared with distances obtained from MS fitting. There are surprising differences between distances obtained with these two methods; in this paper we explore possible explanations for them.

MS fitting relies upon the Vogt-Russell theorem that the location of a star in the H-R diagram is uniquely specified by its mass, composition, and age. This implies that we can infer the distance of a given cluster by comparing the apparent magnitudes of cluster stars with the absolute magnitudes of stars with known composition and distance. There are several possible approaches. Unevolved lower MS field stars with known distances or a cluster (such as the Hyades) of known distance can be used to construct an empirical MS. The distance to the cluster is inferred from the vertical shift needed to line up the cluster MS with the empirical MS. Clusters can also be compared with theoretical isochrones calibrated on the Sun; the latter method requires a

color calibration that relates the model effective temperatures to the observed colors.

Most nearby open clusters are close to the Sun in metal abundance, which minimizes uncertainties in the distance scale from variations in composition. There is also a large database of fundamental effective temperature measurements for stars near the solar  $[\text{Fe}/\text{H}]$ , so the color calibrations should be relatively reliable. The nearby open clusters have also been extensively studied for membership, photometry, abundances, and reddening. For all of these reasons, the open cluster distance scale has not been regarded as controversial, and evidence that MS fitting yields incorrect distances could have significant astrophysical importance.

The *Hipparcos* mission has resulted in a large increase in the number of open cluster stars with measured parallaxes. This data allows the distance scale inferred from MS fitting to be compared with the distance scale inferred from trigonometric parallaxes. The recently announced *Hipparcos* determination of the mean parallax of the Pleiades cluster gives  $8.61 \pm 0.23$  mas (van Leeuwen & Hansen Ruiz 1997a). This corresponds to a distance of  $116 \pm 3$  pc, or a distance modulus of  $5.32 \pm 0.06$  mag. Traditional determinations of the Pleiades distance (e.g., VandenBerg & Bridges 1984; Soderblom et al. 1993), comparing the cluster's main sequence to that of nearby stars, lead to a distance modulus of about 5.6 mag ( $d \sim 130$  pc;  $\pi \sim 7.7$  mas). Thus, the *Hipparcos* parallax, being almost 1 mas larger than expected,

<sup>1</sup> Based on data from the European Space Agency *Hipparcos* astrometry satellite.

suggests that the Pleiades cluster stars are systematically  $\sim 0.3$  mag fainter than we have thought up to now.

Parallaxes for stars in other clusters have also been measured, and the results are compared in Table 1 with those obtained from MS fitting (data are from Perryman et al. 1997; Mermilliod et al. 1997; Robichon et al. 1997). The standard reddening for the clusters is also indicated, along with a notation of whether or not differential reddening is present. Column (2) lists the cluster  $[\text{Fe}/\text{H}]$  values from Boesgaard & Friel (1990) and Friel & Boesgaard (1992); we have adopted their abundance scale for the clusters in the present study (see § 4). Mermilliod et al. (1997) and Robichon et al. (1997) concluded that there is no simple explanation for the discrepancies between the MS-fitting and *Hipparcos* distances, and that all of the possible classes of solutions appeared unsatisfactory.

We note that a second calculation of the distance to Praesepe has been performed by van Leeuwen & Hansen Ruiz (1997b), who find a distance modulus of  $6.49 \pm 0.15$ —in disagreement with both MS-fitting and the Mermilliod et al. (1997) *Hipparcos* distance. For the purposes of this paper, we have adopted the Mermilliod distance; if we were to adopt the van Leeuwen & Hansen Ruiz (1997b) distance to the cluster, we would have to add Praesepe to the list of clusters with a significant ( $2\sigma$ ) discrepancy between the MS-fitting and *Hipparcos* distance scales.

Column (4) in Table 1 lists the values cited as “Lynga” by Mermilliod et al. (1997) and Robichon et al. (1997). We note that these are *apparent* distance moduli, needing considerable (up to 1.2 mag) corrections for extinction, and cannot be directly compared with the distance moduli  $(m - M)_0$  calculated from the *Hipparcos* parallaxes. The next column in Table 1 lists the distance moduli that correspond to the cluster distances given in the Lyngå (1987) Catalogue. These distances come from a variety of sources, are still scaled to a Hyades distance modulus of 3.01 mag, and need corrections for each cluster’s metallicity. One motivation for our study is to place MS-fitting distances for open clusters on a consistent scale. In a paper in preparation, we have found that the MS-fitting distances to some of the more distant open clusters are substantially different from the Lynga distances and in marked disagreement with the *Hipparcos* parallax distances. A second question is the precision of MS-fitting estimates; we will show that accuracy at the

0.05 mag level is possible for well-studied systems. Our results for the clusters studied in this paper are given in column (6).

Discrepancies between the MS-fitting distances and the *Hipparcos* distances could arise from several sources. As indicated above, one possibility is that the MS-fitting distances need to be rederived on a consistent scale. Another possibility is that some of the basic properties of well-studied open clusters, such as composition, age, or reddening, need to be revised. If neither of these possibilities can reconcile the distance scales, then we are left with one of two important conclusions: either there are fundamental problems with MS fitting, or there are unrecognized systematic errors in the *Hipparcos* parallaxes themselves.

These issues are important for other questions as well. For example, recently proposed revisions to the globular cluster distance and age scales, based on *Hipparcos* parallaxes of subdwarfs, rely on the same MS fitting technique that gives rise to the puzzling distances to open clusters (Reid 1997; Gratton et al. 1997; Chaboyer et al. 1998; but see also Pont et al. 1998).

In this paper we address the essential issues raised above. The Pleiades, Praesepe, and  $\alpha$  Per are well suited to a more detailed examination. There is good membership information and multicolor photometry for all three;  $\alpha$  Per is a system with an age comparable to that of the Pleiades (50 Myr versus 100 Myr) and therefore can provide a test of age-related effects. We have also examined the Coma Ber star cluster, which has a low quoted error for its *Hipparcos* distance. In a companion paper (Soderblom et al. 1998; hereafter Paper II), we have searched for field stars with accurate parallaxes and anomalous positions in the H-R diagram.

We begin by describing the theoretical models that we use and the open cluster data in § 2. In § 3 we begin with a comparison of the Pleiades, Praesepe, and  $\alpha$  Per in different colors. We then use the Hyades cluster to test the zero-point of our distance scale, to check on the shape of the isochrones in the observational color-magnitude diagram, and to determine the sensitivity of distance estimates in different colors to changes in metal abundance. We then derive distance modulus estimates at both solar  $[\text{Fe}/\text{H}]$  and the individual abundances inferred from high-resolution spectroscopy for the Pleiades, Coma Ber, Praesepe, and  $\alpha$  Per

TABLE 1  
OPEN CLUSTER PARAMETERS

Cluster (1)	$[\text{Fe}/\text{H}]$ (2)	$(m - M)$ Apparent (3)	$(m - M)_0$ Lynga (4)	$(m - M)_0$ <i>Hipparcos</i> (5)	$(m - M)_0$ This paper (6)	$E(B - V)$ (mag) (7)
Hyades .....	+0.13	3.01	3.01	$3.33 \pm 0.01$	$3.34 \pm 0.04$	0.00
Coma Ber .....	-0.07	4.49	4.49	$4.73 \pm 0.04$	$4.54 \pm 0.04$	0.00
Pleiades .....	-0.03	5.61	5.48	$5.33 \pm 0.06$	$5.60 \pm 0.04$	0.04
IC 2602 .....	...	6.02	5.89	$5.84 \pm 0.07$	...	0.04
IC 2391 .....	...	5.96	5.92	$5.83 \pm 0.08$	...	0.01
Praesepe .....	+0.04	5.99	5.99	$6.24 \pm 0.12$	$6.16 \pm 0.05$	0.00
$\alpha$ Per .....	-0.05	6.36	6.07	$6.33 \pm 0.09$	$6.23 \pm 0.06$	0.10 <sup>a</sup>
Blanco 1 .....	...	6.97	6.90	$7.01 \pm 0.26$	...	0.02
IC 4756 .....	...	8.58	7.94	$7.30 \pm 0.19$	...	0.20 <sup>a</sup>
NGC 6475 .....	...	7.08	6.89	$7.32 \pm 0.19$	...	0.06
NGC 6633 .....	...	8.01	7.47	$7.32 \pm 0.34$	...	0.17 <sup>a</sup>
Stock 2 .....	...	8.62	7.41	$7.50 \pm 0.32$	...	0.38 <sup>a</sup>
NGC 2516 .....	...	8.49	8.07	$7.71 \pm 0.15$	...	0.13
NGC 3532 .....	...	8.53	8.40	$8.10 \pm 0.36$	...	0.04

<sup>a</sup> Variable reddening.

using several different methods and both  $B-V$  and  $V-I$ . The Pleiades and Coma Ber are found to be in disagreement with the *Hipparcos* distance scale. We discuss the sensitivity of our results to age, composition, and reddening in § 4, and present evidence that the *Hipparcos* parallaxes may contain small-scale ( $\sim 1^\circ$ ) systematic effects  $\sim 1$  mas in size, large enough to cause the Pleiades parallax discrepancy. Our conclusions are given in § 5.

## 2. METHOD AND DATA

### 2.1. Theoretical Model Parameters

Theoretical stellar models were constructed with the Yale stellar evolution code for a range of compositions. The nuclear reaction cross sections are from Bahcall, Pinsonneault, & Wasserburg (1995). We use the Saumon, Chabrier, & van Horn (1995) equation of state for temperatures less than  $10^6$  K; this EOS is superior to the treatment in earlier versions of the Yale evolution codes for the conditions present in low-mass stars. The fully ionized EOS in the Yale code was used for higher temperatures; in numerical tests this produced a MS indistinguishable from that obtained with the OPAL EOS (Rogers, Swenson, & Iglesias 1996).

Model atmospheres from R. L. Kurucz (1991a, private communication) were used as a surface boundary condition; these are available for a range of metal abundances. We also constructed models (for solar composition only) using a grid of atmospheres kindly provided by F. Allard (see Allard et al. 1997 for a review). R. L. Kurucz (1991b, private communication) supplied molecular opacities for temperatures of less than  $10^4$  K, and OPAL opacities (Rogers & Iglesias 1992) were used for higher temperatures. The mixing length ( $\alpha = 1.735$ ) and helium abundance ( $Y = 0.2704$ ) were calibrated by requiring that a solar model have the radius and luminosity of the Sun at the age of the Sun.

We then generated models from  $[\text{Fe}/\text{H}] = -0.3$  to  $[\text{Fe}/\text{H}] = +0.2$  in 0.1 dex increments. At each metal abundance, we ran a grid of masses from 0.2 to  $1.6 M_\odot$  in  $0.1 M_\odot$  increments. Helium abundances for nonsolar  $[\text{Fe}/\text{H}]$  were obtained by combining the solar helium abundance with an assumed  $\Delta Y/\Delta Z = 2$ . Isochrones were constructed at a variety of ages, to account for the pre-MS nature of the lower mass stars in the young clusters. We also constructed a set of models with solar  $Z$  but enhanced helium ( $Y = 0.37$ ). The Yale color calibration (Green 1988) was used to convert from the theoretical ( $L$ ,  $T_{\text{eff}}$ ) plane to the observational (magnitude, color) plane in  $B-V$  and  $V-I$ .

### 2.2. Field Star and Cluster Data

For the open clusters, the distance modulus estimates from *Hipparcos* parallaxes are taken from Mermilliod et al. (1997) and Robichon et al. (1997). To perform MS fitting, we restricted the sample to stars with  $B-V$  in the range of 0.5–0.9. Distance modulus estimates for early-type stars can be affected by the assumed cluster age, and  $V-I$  becomes a poor temperature indicator; we therefore excluded stars with  $B-V$  colors of less than 0.5. The color calibrations become unreliable for late-type stars; we therefore excluded stars with  $B-V$  colors greater than 0.9 from our MS-fitting estimates. Our choice of this color interval also makes our distance estimates insensitive to the adopted cluster ages.

For the photometry of open cluster stars, data were taken from several sources. For the Hyades, we used cluster

members (as determined by Perryman et al. 1997) that were considered to be single stars by Griffin et al. (1988). We restricted the sample to stars with RI photometry (on the Johnson system) from Mendoza (1967). Since the *Hipparcos* sample is magnitude-limited, including other stars in common between the Perryman and Griffin papers did not result in increasing the sample size significantly in the color range of interest, and including additional stars with RI colors measured in other systems raises the possibility of systematic color effects. Individual parallaxes for the Hyades stars were used to infer individual  $M_V$  values and correct for depth effects.

For both the Pleiades and Praesepe, photometry for the upper-MS stars was taken from Mendoza (1967). Additional data for  $\alpha$  Per are from Stauffer et al. (1985, 1989), Prosser (1992), Mitchell (1960), and Prosser (1994b). Photometry for the lower-MS stars in the Pleiades was taken from Stauffer (1980, 1982a, 1984), Johnson & Mitchell (1958), and Landolt (1979). Additional photometry for Praesepe was also taken from Uggren, Weis, & DeLuca (1979), Weis (1981), Stauffer (1982b), and Johnson (1952). Photometry for the Coma cluster was taken from Johnson & Knuckles (1955) and Mendoza (1967).

The Mendoza open cluster RI photometry is on the Johnson system, while the other open cluster RI data is on the Kron system; both the isochrones and the field-star data are on the Cousins system.

For the reddening, we adopted  $E(B-V) = 0$  for the Hyades (Crawford & Perry 1966) and Praesepe (Crawford & Barnes 1969). For the Pleiades we adopted  $E(B-V) = 0.04$ , and we used individual reddenings for a small number of highly reddened stars (Crawford & Perry 1976; Breger 1986; Stauffer & Hartmann 1987). The system  $\alpha$  Per has patchy and variable differential reddening that is apparent in the cluster color-magnitude diagram; we adopted  $E(B-V) = 0.10$  (see Crawford & Barnes 1974; Prosser 1994a). We corrected the  $V$  magnitudes and different colors for reddening as follows (Allen 1973; Bessell & Brett 1988):  $A_V = 3.12E(B-V)$ ,  $E(V-I)_{\text{Cousins}} = 1.25E(B-V)$ ,  $E(V-I)_{\text{Kron}} = 1.5E(B-V)$ , and  $E(V-I)_{\text{Johnson}} = 1.75E(B-V)$ .

The impact of reddening on distance modulus estimates in different colors is discussed in § 4. The reddening-corrected  $(V-I)_J$  and  $(V-I)_K$  were converted to Cousins  $(V-I)_C$  using the transformations in Bessell (1979) and Bessell & Weis (1987), respectively:  $(V-I)_C = 0.778(V-I)_J$ ,  $0 < (V-I)_J < 2$  (true for all Mendoza stars in this color range), and  $(V-I)_C = 0.227 + 0.9567(V-I)_K + 0.0128(V-I)_K^2 - 0.0053(V-I)_K^3$ .

## 3. MAIN-SEQUENCE FITTING

Most work on cluster distances has used  $B-V$  color as an effective temperature index. In Figure 1 we compare the Pleiades to  $\alpha$  Per and Praesepe at the *Hipparcos* distances in the observational ( $M_V$  versus  $B-V$ ) plane. Both Praesepe and  $\alpha$  Per are distinctly above the Pleiades. This result is as disturbing as the discrepancies in Table 1, because the measured  $[\text{Fe}/\text{H}]$  of the three clusters are within 0.1 dex, implying that the cluster main sequences should be very close in this diagram (within 0.1 mag).

The  $B-V$  color is highly metallicity sensitive, and the distances inferred from  $B-V$  are therefore quite sensitive to the adopted cluster  $[\text{Fe}/\text{H}]$  values. If the true cluster abundances deviate from the currently accepted values, then one

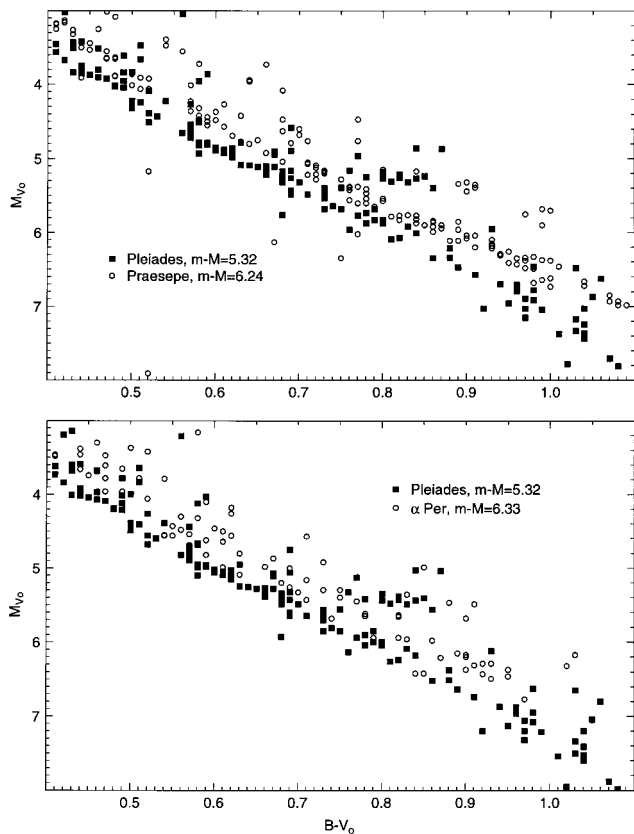


FIG. 1.—The Pleiades compared with Praesepe (*top panel*) and  $\alpha$  Per (*bottom panel*) in  $B-V$ . Stars have been shifted by the *Hipparcos* distances given in Table 1; photometry sources are listed in § 2. The Pleiades stars are shown by filled symbols; stars in the other clusters are shown by open symbols.

might expect the cluster main sequences to be closer in a less metallicity sensitive index, such as  $V-I$ . The clusters are compared in  $(V-I)_C$  in Figure 2. Praesepe is closer to the Pleiades in this index, which suggests that part of the difference seen in Figure 1 is caused by a difference in chemical composition. However, the two cluster main sequences are still well separated in  $V-I$ , and the difference between the Pleiades and  $\alpha$  Per is the same in both colors. These figures illustrate both the magnitude of the problem and the difficulty in explaining it by either metallicity or age. To quantify this problem, we need to determine the sensitivity of distances based upon temperature measurements from  $B-V$  and  $V-I$  to changes in composition.

### 3.1. Theoretical Isochrones and Field MS Data

In Figure 3 we show theoretical isochrones for 1 Gyr populations with different abundances. The top, middle, and bottom panels show the theoretical plane,  $V-I$ , and  $B-V$ , respectively; the Yale color calibration was used for the bottom two panels. The width of the MS is different in each; 0.5 dex in  $[\text{Fe}/\text{H}]$  produces a range of  $\sim 0.3$  mag in the theoretical plane,  $\sim 0.45$  dex in  $V/(V-I)$ , and  $\sim 0.6$  dex in  $V/(B-V)$ . Helium variations affect the isochrones identically in all three planes: a 0.1 increase in  $Y$  produces a 0.28 mag decrease in the locus of the main sequence. The isochrones are nearly parallel across the entire color range of interest. The Alonso, Arribas, & Martinez-Roger (1996; hereafter AAR) color calibration is an alternate method of converting from the theoretical to the observational plane.

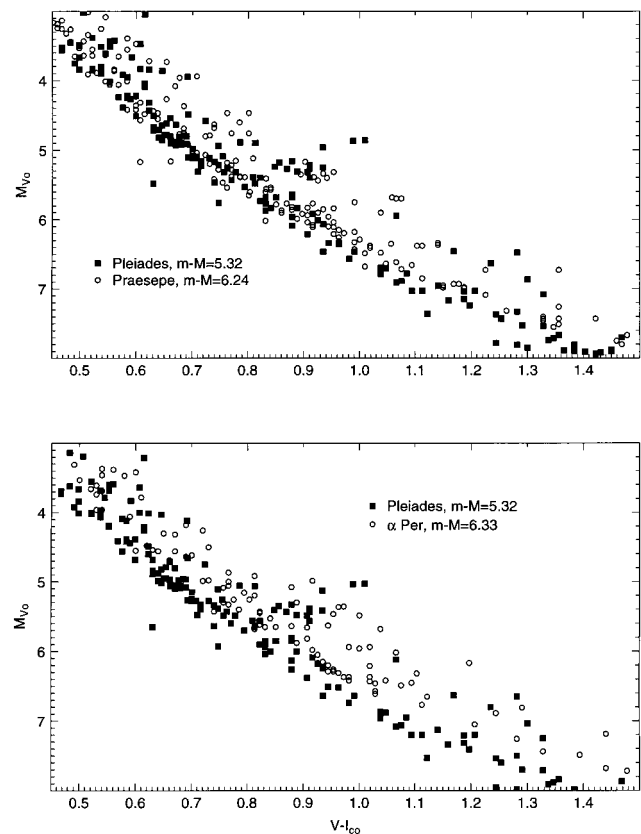


FIG. 2.—The Pleiades compared with Praesepe (*top panel*) and  $\alpha$  Per (*bottom panel*) in  $(V-I)_C$ . Stars have been shifted by the *Hipparcos* distances given in Table 1; Johnson and Kron  $V-I$  have been converted to Cousins  $V-I$ , as described in § 2. The Pleiades stars are shown by filled symbols; stars in the other clusters are shown by open symbols.

The AAR color calibration is based on an application of the infrared flux method, and it can be used to derive the sensitivity of different color indices to changes in metal abundance. The  $[\text{Fe}/\text{H}]$  sensitivity of  $B-V$  in AAR is comparable to that in the Yale color calibration, but AAR find that  $V-I$ , at least in the Johnson system, is metallicity independent; that is, the changes in a  $V-I$ -based color-magnitude diagram should faithfully reflect changes in the theoretical H-R diagram. The Hyades and Praesepe clusters provide support for the AAR findings on the metallicity sensitivity of  $V-I$ , at least for systems near solar metal abundance.

If we adopt the Yale color calibration, a 0.1 dex increase in  $[\text{Fe}/\text{H}]$  produces a 0.12 mag decrease in  $M_V$  at fixed  $B-V$  and a 0.09 mag decrease in  $M_V$  at fixed  $V-I$ . This would imply, for example, that the Hyades (at  $[\text{Fe}/\text{H}] = +0.15$ ) would lie 0.18 mag above a solar-composition isochrone in  $B-V$  and 0.135 mag above a solar-composition isochrone in  $V-I$ . If the metallicity sensitivity of AAR is adopted, then a 0.1 dex increase in  $[\text{Fe}/\text{H}]$  produces a 0.13 mag decrease in  $M_V$  at fixed  $B-V$  and a 0.06 mag decrease in  $M_V$  at fixed  $V-I$ . The Yale color calibration implies that a color-color diagram in  $B-V$  and  $V-I$  should be metallicity insensitive, because both indices are metallicity sensitive (albeit to slightly different degrees); the AAR results would produce a wider spread in a color-color diagram, because  $B-V$  is much more metallicity sensitive than  $V-I$ .

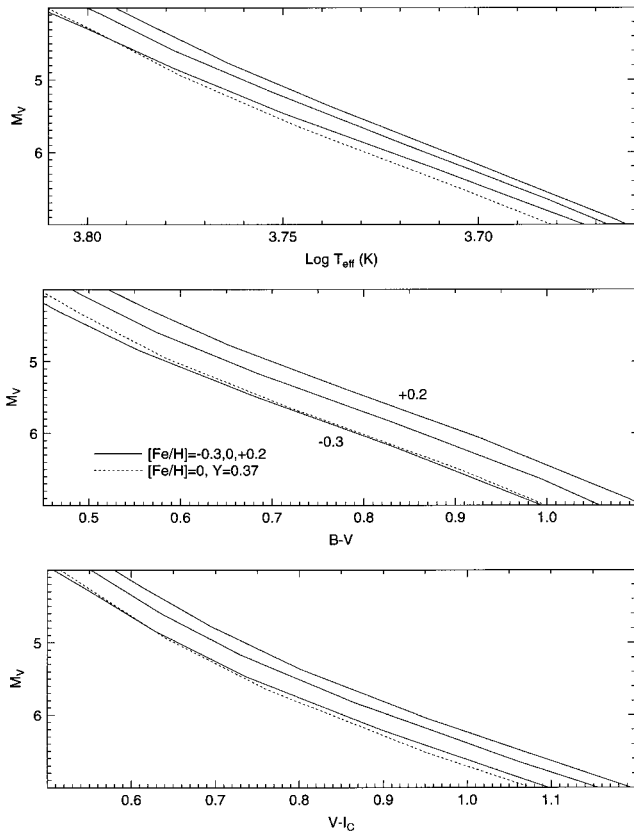


FIG. 3.— $M_V$  for 1 Gyr as a function of  $\log T_{\text{eff}}$  (top panel),  $B-V$  (middle panel), and  $(V-I)_C$  (bottom panel). In each panel, the bottom, middle, and top solid lines show  $[\text{Fe}/\text{H}] = -0.3, 0$ , and  $+0.2$ , respectively; the dashed line shows a  $[\text{Fe}/\text{H}] = 0$  isochrone with a helium abundance of 0.37 (0.1 higher than the solar calibrated value).

The local field stars span a range in  $[\text{Fe}/\text{H}]$ , with the bulk of the F and G stars in the Gliese catalog spanning a range from  $-0.3$  to  $+0.2$  (Wyse & Gilmore 1995; see also McWilliams 1997). We therefore expect a significant intrinsic width to the field star MS as well as a population of binary stars above the MS. The relative width of the MS in the  $B-V$  and  $V-I$  planes can be used as a test of the relative sensitivities of the two color indices to  $[\text{Fe}/\text{H}]$ .

The *Hipparcos* mission has provided parallaxes accurate to 5% or better for a significant number of lower-MS stars. There is a smaller sample (680 stars) with both  $B-V$  and  $V-I$  colors; the field MS in both colors is compared with the models in Figure 4. The field MS is much tighter in  $V-I$  than in  $B-V$ , suggesting that much of the spread in Figure 4 is caused by atmospheric effects (the dependence of  $B-V$  color on metal abundance) rather than by interior effects. We therefore expect that there will be systematic differences between the derived distances in  $B-V$  and  $V-I$  if the adopted  $[\text{Fe}/\text{H}]$  for the isochrone departs from that of the star, or cluster, at the 0.07 mag (AAR) or 0.03 mag (Yale) level per 0.1 dex in  $[\text{Fe}/\text{H}]$ . This discrepancy will be in the sense that the  $V-I$  distance will be longer than the  $B-V$  if the true metal abundance is higher and shorter than the  $B-V$  if the true metal abundance is lower.

### 3.2. The Hyades

The Hyades cluster provides an opportunity to check the distances derived from MS fitting against the *Hipparcos*

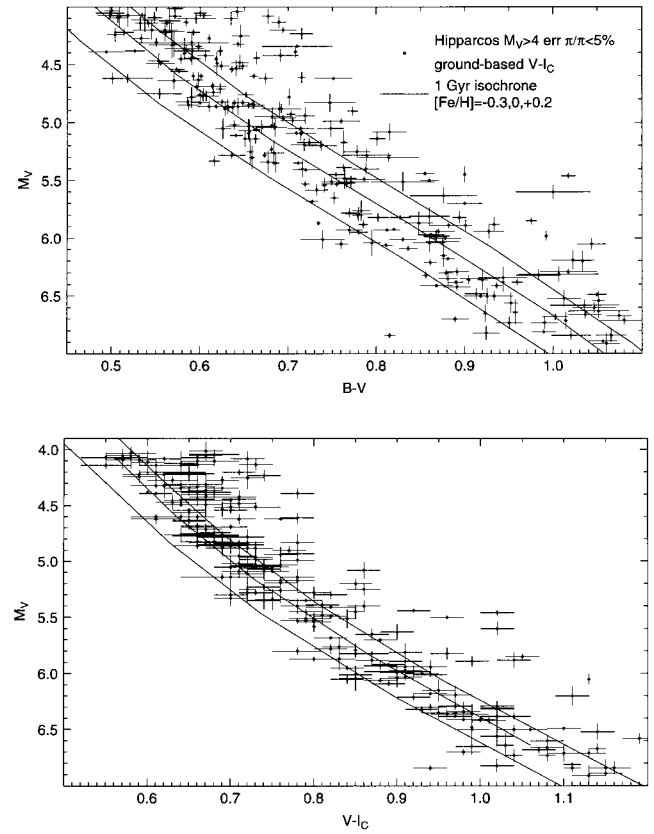


FIG. 4.—Isochrones with an age of 1 Gyr and a range of  $[\text{Fe}/\text{H}]$  are compared with field stars with  $M_V > 4$  and relative parallax errors of less than 5% in  $B-V$  (top panel) and  $(V-I)_C$  (bottom panel). Age effects are responsible for the departure of the data from the isochrone for  $M_V < 5$ . The top, middle, and bottom isochrones are  $[\text{Fe}/\text{H}] = +0.2, 0$ , and  $-0.3$ , respectively.

distance scale for a system with a large number of measured parallaxes spread across a large region of the sky. We can also compare the isochrones in the theoretical plane and in different colors; the Hyades provides a useful check of the sensitivity of the isochrones to changes in metal abundance because it has a metal abundance 0.1–0.2 dex above solar.

Perryman et al. (1997) provides locations for Hyades stars in the theoretical plane as well as isochrones for both solar composition and the Hyades  $[\text{Fe}/\text{H}]$  adopted in that study,  $0.14 \pm 0.05$ . Our 600 Myr isochrones for both  $[\text{Fe}/\text{H}] = 0$  and  $[\text{Fe}/\text{H}] = +0.14$  are compared with the Perryman et al. isochrones in Figure 5. For the range of 3.68–3.84 in  $\log T_{\text{eff}}$ , our  $[\text{Fe}/\text{H}] = 0$  isochrone is on average 0.044 mag brighter than the Perryman et al. isochrones. By comparison, a zero-age MS for  $[\text{Fe}/\text{H}] = 0$  provided by D. A. Vandenberg (1997, private communication) is 0.032 mag fainter than our 100 Myr isochrone, and for  $\log T_{\text{eff}} > 3.75$ , the Yale and Vandenberg isochrones agree to within 0.008 mag. This comparison indicates that systematic differences between different isochrones are at or below the 0.04 mag level overall and agree to within 0.03 mag near the temperature of the Sun.

The Hyades MS of Perryman et al. (1997) is 0.164 mag brighter than their solar  $[\text{Fe}/\text{H}]$  isochrone in this temperature interval; their isochrone with  $[\text{Fe}/\text{H}] = +0.14$  and solar-scaled helium would be too faint to be consistent with the data. They were therefore forced to adopt a sub-solar helium abundance (0.26) in order to reproduce the

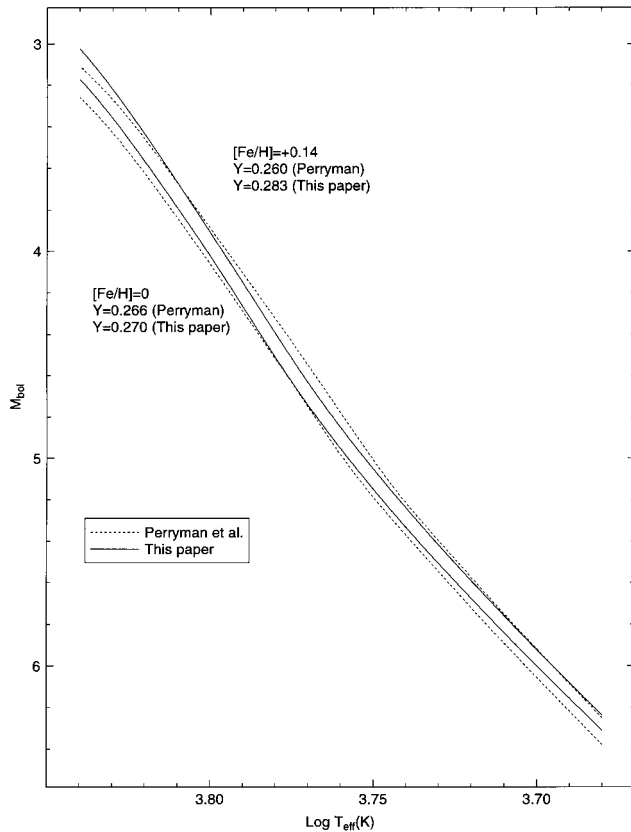


FIG. 5.—Theoretical 600 Myr isochrones in the  $M_{\text{bol}}/\log T_{\text{eff}}$  plane for solar  $[\text{Fe}/\text{H}]$  (bottom lines) and Hyades  $[\text{Fe}/\text{H}]$  (top lines). Solid lines are from this paper, dashed lines are from Perryman et al. (1997).

observed Hyades MS. Our  $[\text{Fe}/\text{H}] = +0.14$  isochrone with  $Y = 0.283$  is 0.017 mag fainter than the Hyades MS from Perryman et al. (1997); this implies that our models are consistent with the Hyades having the  $[\text{Fe}/\text{H}]$  inferred from high-resolution spectroscopy and  $\Delta Y/\Delta Z = 2$ . This result is obtained largely because our solar-composition isochrone is slightly brighter than the Perryman et al. (1997) isochrone; we constructed isochrones with different helium and verified that the changes in the position in the theoretical H-R diagram resulting from changes in  $Y$  and  $Z$  agree with the offsets in Perryman et al. to better than 5%. We obtain similar results when fitting in the observational H-R diagram using  $B-V$  and  $V-I$ . This illustrates the importance of small effects when inferring helium abundances based on H-R diagram position.

The absolute  $V$  magnitudes of single stars and binaries in the Hyades are shown as a function of  $B-V$  and  $V-I$  in Figure 6. Half of the stars are binaries, and the binaries scatter systematically above the single stars in the color-magnitude diagram. For comparison, we show the Schwan (1991) empirical MS for the Hyades in  $B-V$ , shifted to a distance of 3.33. We also derived an empirical fit to the single-star sequence in the  $V-I$  plane, which is compared with the cluster data. The Hyades abundance isochrones are shifted up in the H-R diagram by 0.18 mag in  $B-V$  and 0.135 mag in  $V-I$  relative to a solar-abundance isochrone for the metallicity sensitivity in the Yale color calibration. If the metallicity sensitivity of AAR is adopted, the Hyades isochrones are 0.19 mag above the solar  $[\text{Fe}/\text{H}]$  isochrones in  $B-V$  and 0.09 mag above the solar  $[\text{Fe}/\text{H}]$  isochrones in

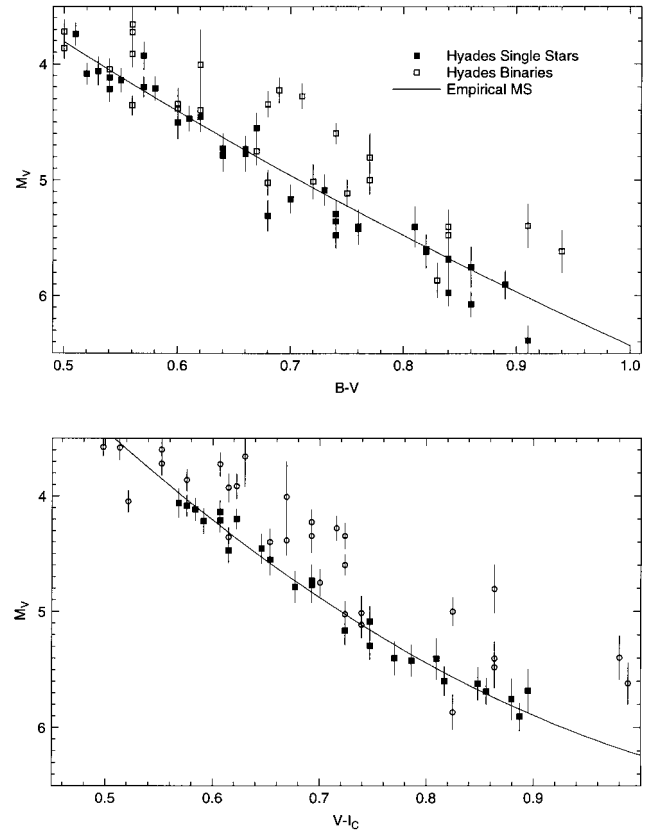


FIG. 6.— $M_V$  as a function of  $B-V$  (top panel) and  $(V-I)_C$  (bottom panel) for Hyades members with *Hipparcos* parallax measurements and  $(B-V) > 0.5$ . Photometry sources are listed in § 2. Filled circles show single stars; open circles show binaries from Griffin et al. (1988). The empirical fits to the single-star MS used in this paper are shown by solid lines.

$V-I$ . A slight mismatch between the shape of the isochrones and the empirical MS is present, and the distance modulus estimates from the isochrones are clearly close to the *Hipparcos* distance scale.

We derived a distance modulus estimate for each of the 35 single stars in our sample; the average is 3.36, with a rms deviation of 0.16. Since the average error in  $M_V$  is 0.13, color errors are contributing little to the overall scatter in the diagram. Since the parallax errors can be correlated, the error in the mean scales as  $N^{-0.35}$ , not  $N^{-0.5}$  (Lindgren 1988, 1989); the formal error in the mean distance modulus estimate is therefore 0.05. Because of the nearness of the Hyades, the mean distance modulus estimate will depend on the subset of stars used in the comparison, and therefore the difference between this estimate and the cluster mean of  $3.33 \pm 0.01$  is not problematic.

The difference  $M_V(\text{observed}) - M_V(\text{predicted})$  for both colors is shown for the single stars as a function of color in Figure 7; the difference between the isochrones and the empirical MS is also shown. For the Yale color calibration, the mean for  $B-V$  is  $-0.04$ , implying a distance modulus of 3.32; the mean for  $V-I$  is  $+0.05$ , implying a distance modulus of 3.41. The dispersion about the mean in both cases is 0.13, consistent with the errors in the absolute magnitudes.

The discrepancy between the distance estimates in  $B-V$  and  $V-I$  could be reduced, or removed, by an increase in the adopted cluster metal abundance; alternately, it could

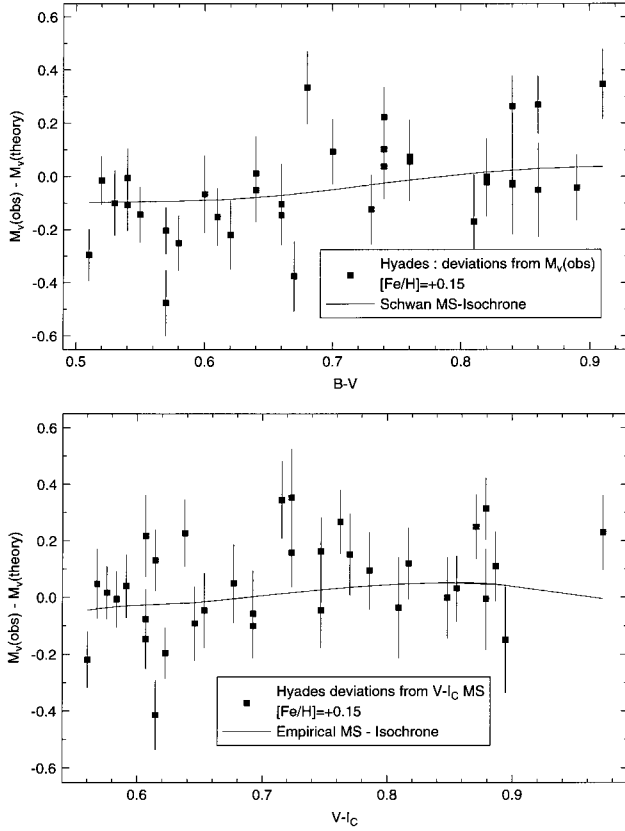


FIG. 7.—Difference between the *Hipparcos*  $M_V$  and that predicted from the isochrones for single Hyades stars with parallax measurements, plotted as a function of  $(B-V)$  (top panel) and  $(V-I)_C$  (bottom panel). The solid lines indicate the corrections as a function of color that were applied to the isochrones for consistency with the shape of the Hyades MS.

indicate that  $B-V$  is more metallicity sensitive and  $V-I$  is less metallicity sensitive than predicted by the models. Since increasing the Hyades metal abundance would cause a disagreement with both the parallax distance to the cluster and the spectroscopic  $[\text{Fe}/\text{H}]$  measurements, we believe that the latter explanation is more likely. If we adopt the derivatives of  $M_V$  with respect to  $[\text{Fe}/\text{H}]$  from AAR, the mean for the  $B-V$  distance is 3.33 ( $-0.03$ ) and the mean for the  $V-I$  distance is 3.36 ( $0.0$ ). The distance we obtain by averaging the two colors is 3.34, in excellent agreement with the *Hipparcos* distance. We therefore adopt the Yale color calibration at solar metal abundance to set the zero-point of the distance scale and the shape of the isochrones, and we adopt the metallicity sensitivity of the AAR color calibration: a 0.1 dex increase in  $[\text{Fe}/\text{H}]$  produces a decrease in  $M_V$  of 0.13 mag at fixed  $B-V$  and 0.06 mag at fixed  $V-I$ .

We have added the binaries and binned the deviations between the individual distance modulus estimates and those predicted from the isochrones. The resulting histograms are plotted in Figure 8. Binaries scatter to systematically lower distance estimates than single stars;  $V-I$  is more affected by this than  $B-V$ . There are two methods that can be used to account for binaries. There is a clear separation between the small mass ratio binaries and the single stars and high mass ratio binaries; the peak in the histogram is resistant to the presence of binaries, although there is a slight bias to lower distance modulus estimates in  $V-I$  because of its higher sensitivity to binaries. The peaks in the histograms of Figure 8 are at  $-0.05$  and  $0$  for  $B-V$

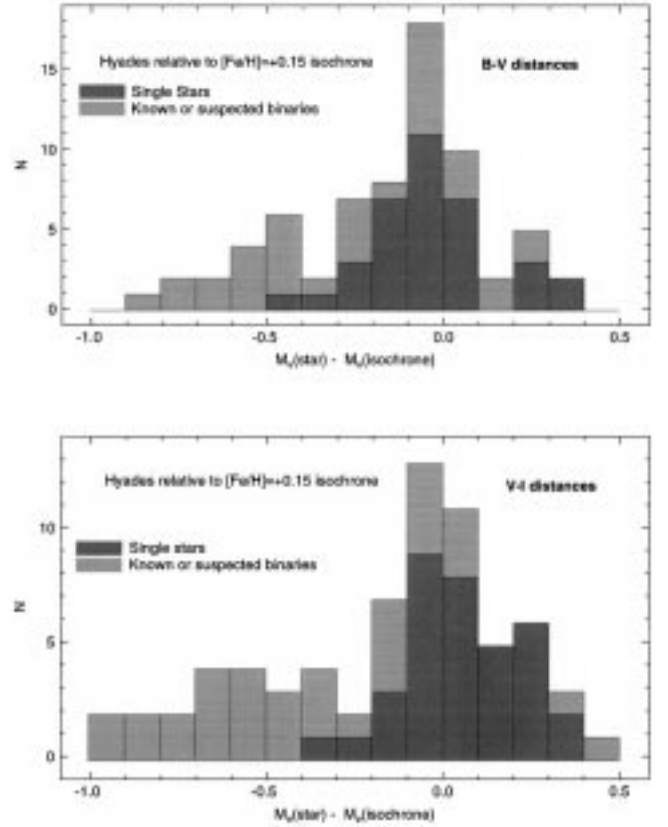


FIG. 8.—Histogram of differences between the *Hipparcos*  $M_V$  and that predicted from the isochrones for  $(B-V)$  (top) and  $(V-I)_C$  (bottom). Data are binned in 0.1 mag intervals; dark bins show single stars, light bins show binaries.

and  $V-I$ , respectively, in good agreement with the single-star averages of  $-0.03$  and  $0$ . Alternately, the distance modulus estimates can be ranked and stars more than 0.2 mag above and below the histogram peak excluded, and the median distance modulus estimate can be inferred. Medians inferred with this technique are also  $-0.05$  and  $0.0$  for  $B-V$  and  $V-I$ , respectively.

We also compare the distance estimates derived from the isochrones and the distance estimates derived from the empirical Hyades MS with the zero-point adjusted to agree with the isochrones at  $1 M_\odot$  for the different colors. The Hyades MS needs to be corrected for the higher than solar  $[\text{Fe}/\text{H}]$  of the cluster; the  $M_V$  at fixed color for a solar-abundance MS is 0.19 mag higher at fixed  $B-V$  and 0.09 mag higher at fixed  $V-I$ . Therefore, the empirical MS that we adopted at solar metal abundance in  $B-V$  and  $V-I$  are, respectively,  $M_V = -2.75 + [4.03 + 85.7(B-V)]^{0.5}$  and  $M_V = -1.976 + 13.758(V-I) - 5.427(V-I)^2$  (valid only from 0.55 to 0.9 in  $V-I$ ).

For younger clusters, the empirical Hyades MS needs to be corrected for age effects (a 0.04 mag level effect for the Pleiades). We took the difference between our 100 and 600 Myr isochrones and applied it to the relationships given above for the Pleiades. We stress that the distances obtained in this manner have the same zero-point as the isochrones; we are using the shape of the Hyades MS and not its absolute distances, so our distance scale is therefore not tied to the distance to the Hyades (although it is in agreement with the cluster distance as measured by *Hipparcos*).

### 3.3. The Pleiades

In Figure 9 we present histograms of the distance modulus estimates for the Pleiades using different techniques. In the top panels, 100 Myr solar-composition isochrones were used to estimate  $M_V$  from  $B-V$  and  $V-I$ , respectively; in the bottom panels, the empirical Hyades MS was used. The darker bins show hotter stars and the

lighter bins show cooler stars; a discrepancy between the mean of the two is an indication of a deviation between the shape of the isochrone and the cluster CMD. In the isochrone distances, cooler stars give systematically longer distance modulus estimates at the 0.1 mag level; these color trends are removed relative to the Hyades MS fits in the lower panels. The good agreement between different tech-

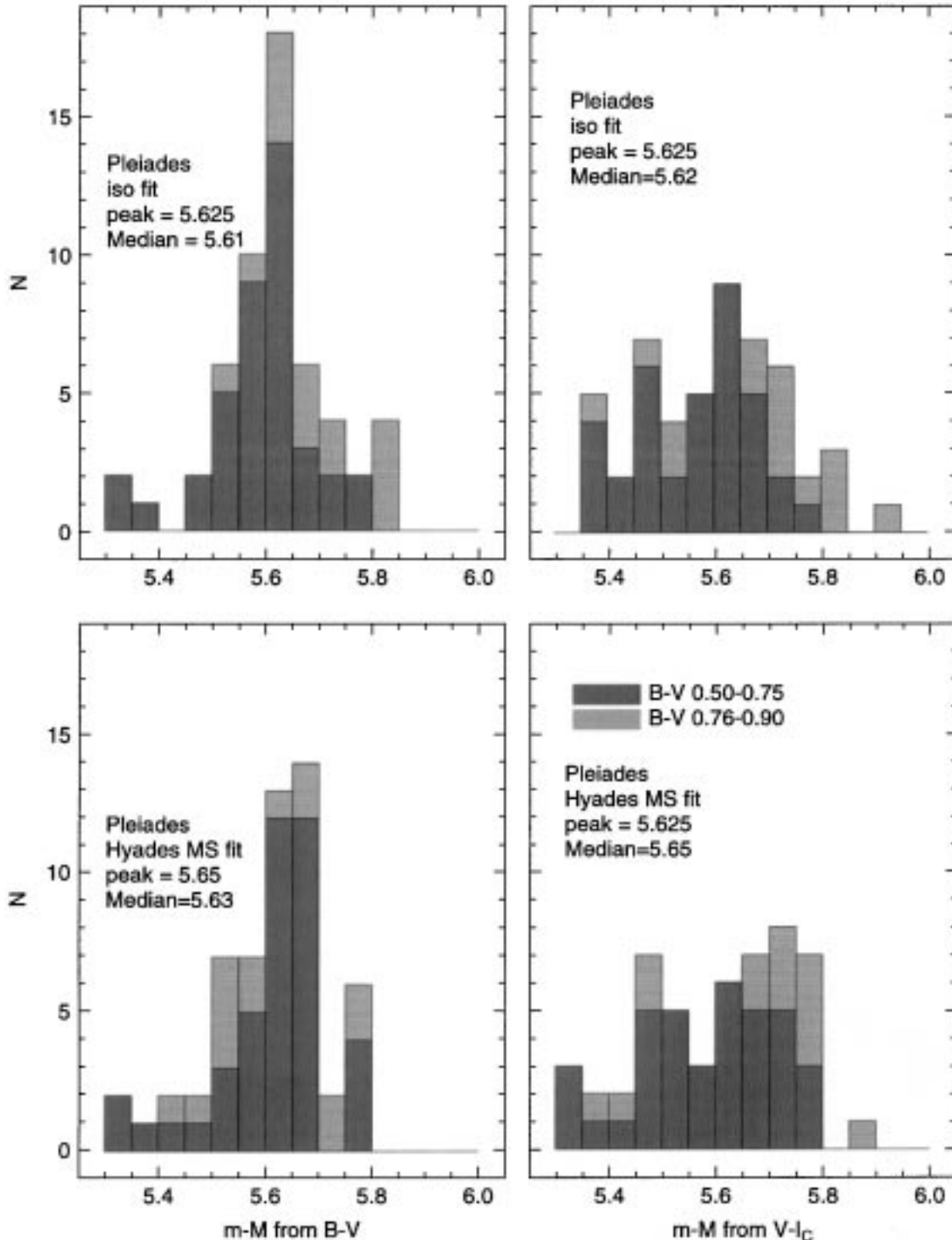


FIG. 9.—Histogram of distance modulus estimates for Pleiades members, binned in 0.05 mag intervals. The isochrones were used for the top panels, while the isochrones were corrected to the shape of the Hyades MS in the bottom panels; those on the left side are distances from the  $(B-V)$  color, and those on the right side are distances from the  $(V-I)$  color predicted from the isochrones for  $(B-V)$  (top) and  $(V-I)_c$  (bottom). Dark bins show stars with  $B-V$  from 0.5 to 0.75; light bins show stars with  $B-V$  from 0.76 to 0.9.



niques suggests that there are small internal errors in MS fitting for systems with good photometry.

An average of the  $V-I$  distance methods yields  $5.63 \pm 0.02$ , while an average of the  $B-V$  distance methods also gives  $5.63 \pm 0.02$ . This should be compared with the Hyades, where a solar-abundance isochrone would give distance modulus estimates that differ by 0.1 mag; this difference is caused by a cluster  $[\text{Fe}/\text{H}]$  0.15 dex higher than solar. If we add the errors in quadrature, this implies that we have a 0.03 mag relative error in the  $B-V$  and  $V-I$  distance estimates, which corresponds to a 0.05 mag error in the photometric  $[\text{Fe}/\text{H}]$ . Boesgaard & Friel (1990) obtained  $[\text{Fe}/\text{H}] = -0.034 \pm 0.024$  for the Pleiades; at this metal abundance, our  $B-V$  and  $V-I$  distance moduli are 5.59 and 5.61, respectively. Our MS-fitting distance to the Pleiades is therefore 5.60, and we estimate that errors in the metal abundance and systematic differences in the MS fitting technique are at the 0.04 mag level.

In Figure 10 we compare the Pleiades to a  $[\text{Fe}/\text{H}] = -0.03$  100 Myr isochrone in both  $B-V$  and  $V-I$ . The isochrone has been shifted to a distance of 5.60. The isochrone is an excellent fit to the cluster CMD. We note that single rapid rotators are on or above the MS in  $V-I$  but below it in  $B-V$ ; this may indicate that the relationship between color and temperature for these stars is different than for slow rotators, and we therefore exclude them from distance estimates in both this cluster and  $\alpha$  Per.

A detailed binary inventory for the Pleiades has recently

been published (Bouvier, Rigaut, & Nadeau 1997; see also Mermilliod et al. 1992), so we can therefore check for the possible impact of binary contamination on our distance estimates. We compare distance estimates for binaries, single stars, and rapid rotators in Figure 11. As expected, stars with very low distance estimates are binaries, and for the high mass ratio binaries,  $B-V$  is less sensitive than  $V-I$ . The broader distributions for  $V-I$  seen in Figure 9 are therefore a reflection of its greater sensitivity to binary contamination. The techniques that we have applied do not appear to be affected significantly; if we use only the single stars, a slightly higher distance of 5.65 is indicated for both colors.

To reproduce the *Hipparcos* distance of 5.33, we would require  $[\text{Fe}/\text{H}] = -0.25$  for  $B-V$  and  $[\text{Fe}/\text{H}] = -0.45$  for  $V-I$ . Reproducing the *Hipparcos* distance to the Pleiades by changing the metal abundance would therefore require a much lower metallicity than that obtained by high-resolution spectroscopy; furthermore, the distance estimates for different colors would be in strong disagreement. Other possibilities are discussed in § 4.

### 3.4. Praesepe

In Figure 12 we present histograms of the distance modulus estimates for Praesepe obtained using different techniques; as for the Pleiades, the top panels are relative to the isochrones (600 Myr for Praesepe) and the bottom panels are relative to the isochrones with the shape adjusted to agree with the empirical Hyades MS. Particularly for

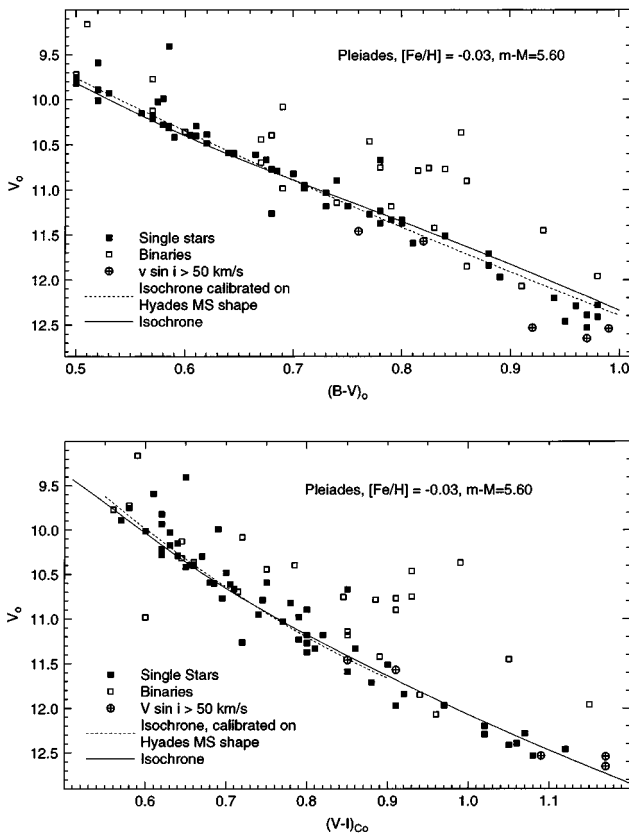


FIG. 10.—100 Myr theoretical isochrones with  $[\text{Fe}/\text{H}] = -0.03$  shifted to a distance of 5.60 compared with the Pleiades in  $(B-V)$  (top) and  $(V-I)$  (bottom). Filled squares show single stars, open circles show binaries from Bouvier, Rigaut, & Nadeau (1997), and open circles with a cross show rapid rotators. Solid lines show the isochrones, and dashed lines show the same isochrones with the Hyades MS shape.

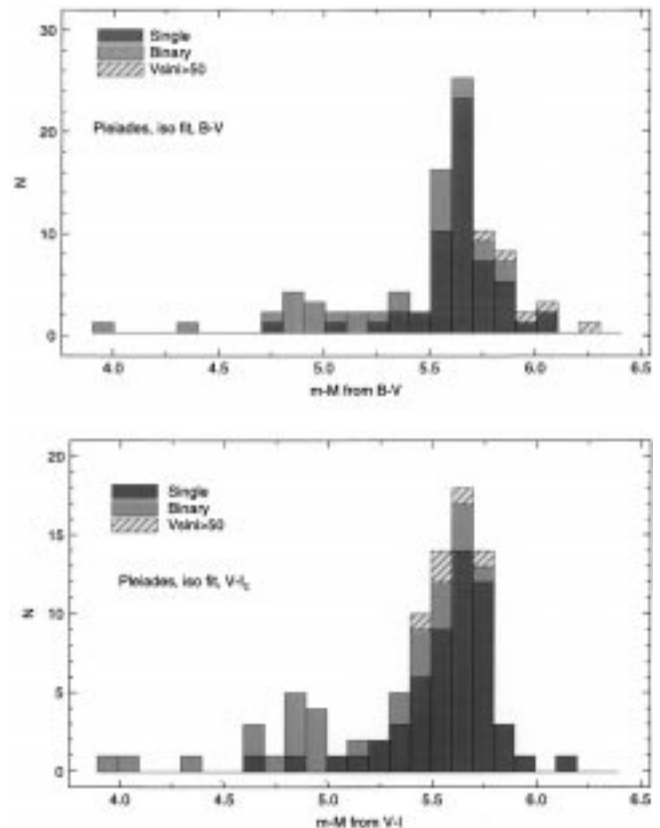


FIG. 11.—Same as the top two panels of Fig. 9, but with a wider color range ( $B-V$  from 0.5 to 1.0) and with data binned in 0.1 mag intervals. Single stars are shown by the dark bins, binaries from Bouvier et al. (1997) are shown by the light bins, and rapid rotators are shown by the striped bins.

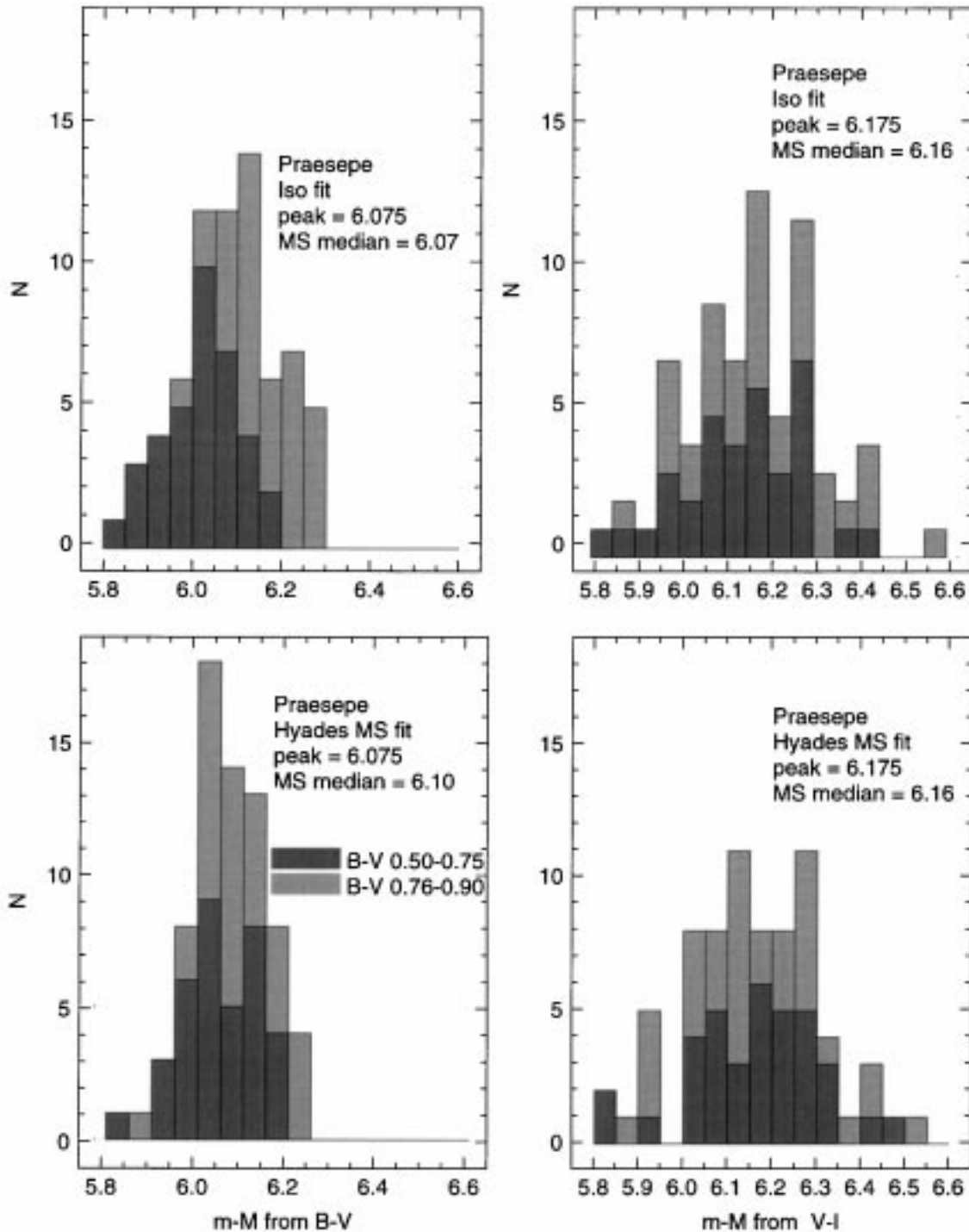


FIG. 12.—Same as Fig. 9, except for Praesepe relative to a 600 Myr isochrone

$B-V$ , there is a clear indication that the distance estimates for the uncorrected isochrones depend on color at the 0.1 mag level; this is more apparent for Praesepe than for the Pleiades largely because the Praesepe sample includes more cool stars than the Pleiades sample. However, the histogram peaks and medians are similar for the uncorrected isochrones and those obtained relative to the shape of the Hyades MS. An average of the  $V-I$  distance methods yields  $6.17 \pm 0.02$ , while an average of the  $B-V$  distance methods yields  $6.08 \pm 0.02$ . This difference is significantly larger than our estimated relative error of 0.03. We there-

fore conclude that the difference between the two is real and indicates that Praesepe is mildly metal rich.

The two distance modulus estimates agree at  $[\text{Fe}/\text{H}] = +0.13$  and a distance modulus of 6.25. The Friel & Boesgaard (1992)  $[\text{Fe}/\text{H}]$  for Praesepe is  $0.04 \pm 0.04$ , while a higher abundance is inferred by some other studies (see § 4.2). At the Friel & Boesgaard (1992)  $[\text{Fe}/\text{H}]$ , the distance modulus is 6.13 in  $B-V$  and 6.19 in  $V-I$ ; we therefore adopt a distance modulus estimate of 6.16 for Praesepe (Fig. 13). This is well within the error bounds of the *Hipparcos* distance estimate of  $6.24 \pm 0.12$ . We conclude that Praesepe

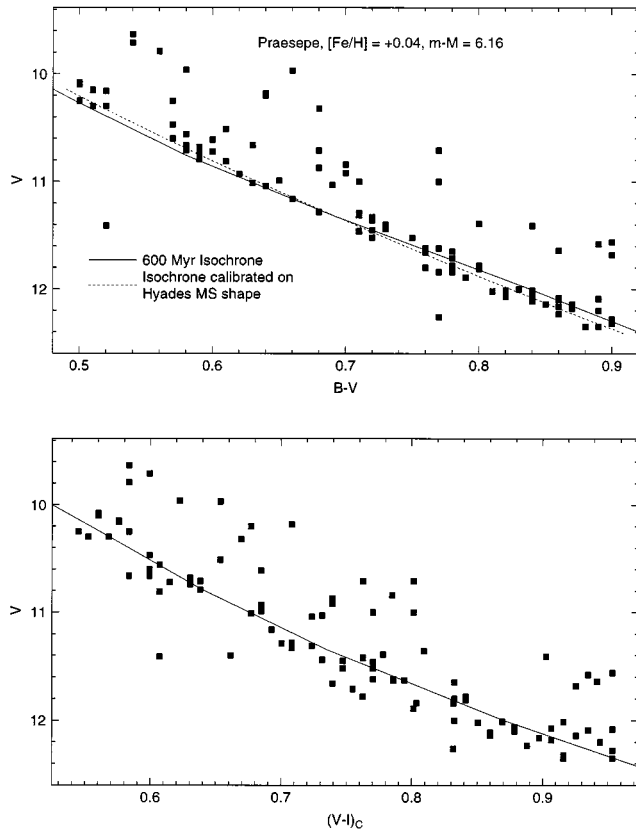


FIG. 13.—600 Myr theoretical isochrones with  $[\text{Fe}/\text{H}] = +0.04$  shifted to a distance of 6.16, compared with Praesepe in  $(B-V)$  (top) and  $(V-I)$  (bottom). Solid lines show the isochrones; dashed lines show the same isochrones with the Hyades MS shape.

is consistent within the errors with the *Hipparcos* distance measurement and that the photometry is consistent with it being more metal rich (at the 0.1 dex level) than the Friel & Boesgaard (1992) estimate.

The dominant source of error in the distance modulus is the metal abundance of the clusters; in general, relative metal abundances can be determined more precisely than absolute metal abundances. Another way of looking at the problem of reconciling the MS fitting and *Hipparcos* distance scales is therefore to look at relative distances in different colors and ask what metal abundance difference is needed to explain the results. The Pleiades and Praesepe are especially difficult to explain in combination. At solar  $[\text{Fe}/\text{H}]$ , the relative distances of these two clusters from MS fitting are 0.45 and 0.54 mag in  $B-V$  and  $V-I$ , respectively. By comparison, the magnitude difference between the two clusters for the *Hipparcos* distance scale is 0.91. If Praesepe is metal rich or the Pleiades is metal poor, then the true difference in distance modulus estimates will be larger than at solar  $[\text{Fe}/\text{H}]$ , with  $B-V$  being more metallicity sensitive than  $V-I$ . Reconciling the relative cluster distances in  $B-V$  and  $V-I$  by changing the metal abundances would require a metallicity difference of 0.35 dex and 0.6 dex, respectively; both are well outside the range of relative metal abundances reported by different investigators.

### 3.5. $\alpha$ Per

$\alpha$  Per is a young system (50 Myr), with a larger overall reddening (0.10) than the other clusters we examine, and with some differential reddening. In Figure 14 we show the distribution in distance modulus estimates in both  $B-V$

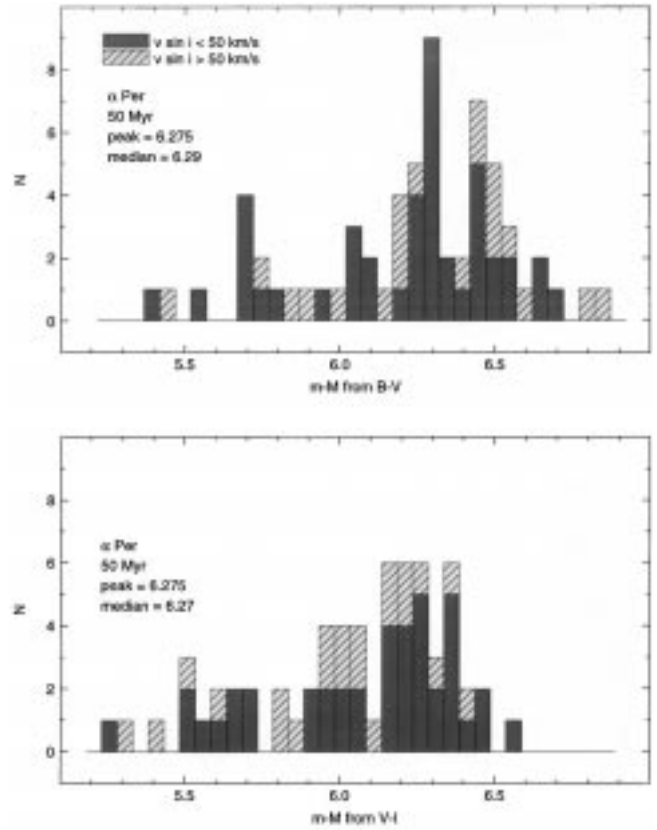


FIG. 14.—Histogram of distance modulus estimates for  $\alpha$  Per members, binned in 0.05 mag intervals. Top panel shows distances from the  $(B-V)$  color, bottom panel shows distances from the  $(V-I)$  color; isochrones with the Hyades MS shape yield similar results, but are not shown. Slow rotators are shown by the dark bins and rapid rotators ( $v \sin i > 49 \text{ km s}^{-1}$ ) are shown by the light bins.

and  $V-I$  relative to a solar-composition 50 Myr isochrone. There is a larger population of rapid rotators in this cluster than in the Pleiades, and they show the same pattern (long distances in  $B-V$  and short distances in  $V-I$ ). A subpopulation of stars at higher distances is present in both colors, with distances systematically higher for  $B-V$  than for  $V-I$ . This could be caused by variable reddening, by rapid rotators with low  $\sin i$ , or by contamination of the sample by nonmembers. Excluding these stars only affects the distance estimates at the 0.02 mag level and does not change the relative distances in the two colors.

There is a well-defined peak in  $B-V$  at a distance of 6.275, and the distribution for  $V-I$  is centered at the same distance; the median of the single stars is at 6.29 and 6.27 for  $B-V$  and  $V-I$ , respectively, giving average distances of 6.28 and 6.27 for the two colors. Therefore, at solar abundance the average cluster distance is 6.28; there is a hint of a mild metal deficiency in the relative distances in the two colors, at the 0.02 dex level. If we adopt the high-resolution abundance  $[\text{Fe}/\text{H}] = -0.05$ , our average distance is 6.23; because the error in the metal abundance is higher for this system than for the others (0.05), the error is larger, 0.06 mag. A 50 Myr isochrone is compared with the cluster in Figure 15. Significantly, there is no evidence for a discrepancy between the MS-fitting and *Hipparcos* distance scales; because both  $\alpha$  Per and the Pleiades are young, this indicates that the problem with the Pleiades is not a consequence of systematic color errors arising from the youth of the system.

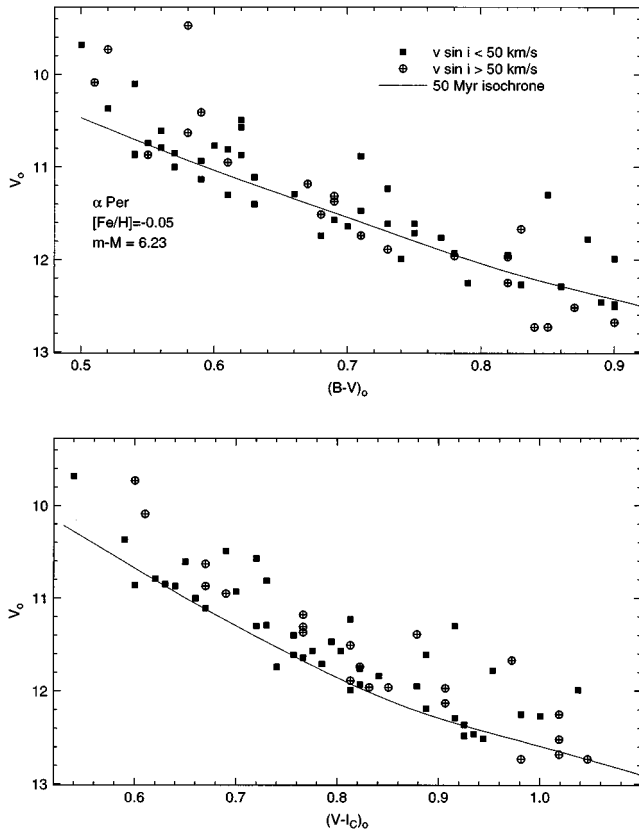


FIG. 15.—50 Myr theoretical isochrones with  $[\text{Fe}/\text{H}] = -0.05$  (solid lines) shifted to a distance of 6.23, compared with  $\alpha$  Per in  $(B-V)$  (top) and  $(V-I)$  (bottom). Slow rotators are shown by filled squares; rapid rotators are shown by open circles with a cross.

### 3.6. Coma Ber

Coma Ber is a sparse cluster with an age comparable to the Hyades; it is mildly metal poor ( $[\text{Fe}/\text{H}] = -0.071 \pm 0.020$ ; see Taylor 1994). Surveys have been undertaken to find low-mass members, and few candidates have been found (for a discussion, see Randich, Schmitt, & Prosser 1996). We used the Johnson & Knuckles (1955) photometry for  $B-V$  and the Mendoza (1967) photometry for  $V-I$ ; we note that the  $V-I$  photometry for the cluster stars listed in RSP differs significantly from that in Mendoza (1967) and is based on an earlier study by Mendoza. The sample size for the color interval used in the other clusters is small (15 stars), so we also included 9 additional stars with  $B-V$  from 0.35 to 0.49 and  $V > 7.5$ . A histogram of the distance estimates from the isochrones is shown in Figure 16. There is a clear peak in the histogram for  $B-V$  at a distance modulus of 4.625 at solar  $[\text{Fe}/\text{H}]$ . The Hyades MS shape yields a peak at a similar distance of 4.675, but with a systematic dependence of the distance estimate on color, i.e., the shape of the Coma Ber and Hyades MS are different for the hotter stars. We therefore adopt the isochrone fit for our distance estimate. Correcting for metal abundance, we get a  $B-V$  distance modulus for Coma Ber of 4.54; given the low quoted error in the cluster  $[\text{Fe}/\text{H}]$ , we estimate an error of 0.04 mag. If we were to adopt a larger uncertainty of 0.05 dex in the cluster  $[\text{Fe}/\text{H}]$ , the error in the distance estimates for all of the clusters we have studied would rise to 0.06 mag. The MS-fitting distance of 4.54 shows a  $3.4 \sigma$  discrepancy with the *Hipparcos* distance if we adopt an error in the MS-fitting distance of

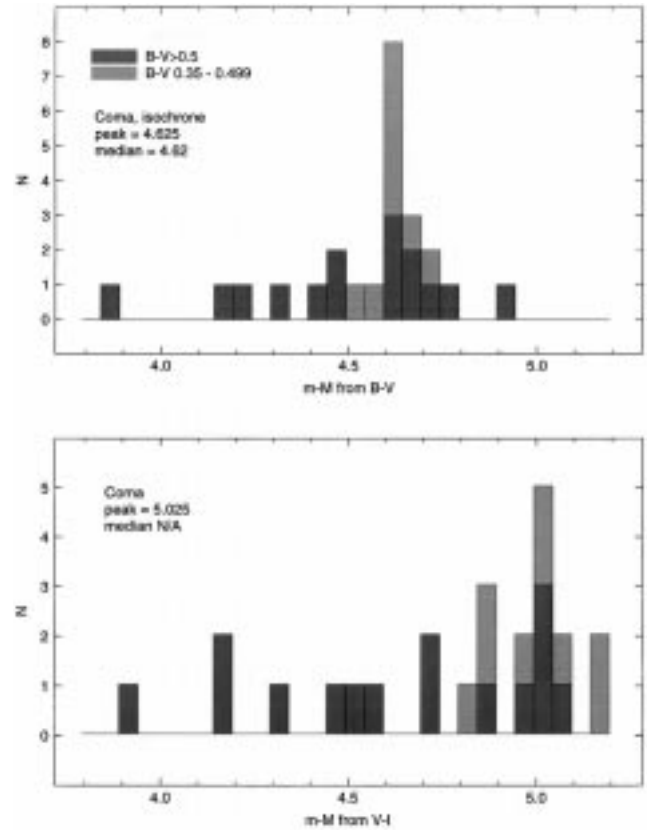


FIG. 16.—Histogram of distance modulus estimates for Coma Ber members, binned in 0.05 mag intervals. The top panel shows distances from the  $(B-V)$  color; bottom panel shows distances from the  $(V-I)$  color. Dark bins show stars with  $(B-V)$  from 0.5 to 0.9, which corresponds to the color interval used for the other clusters. The light bins show hotter stars, with  $(B-V)$  from 0.35–0.499. Note that for the cooler stars, there is no well-defined peak for  $(V-I)$ , and that the overall peak disagrees significantly with the *Hipparcos* and  $(B-V)$  distances (see text).

0.04, and  $2.6 \sigma$  if we adopt an error in the MS-fitting distance of 0.06.

The behavior of the cluster in  $V-I$ , however, is puzzling. There is no well-defined peak for the cool stars, and the hotter stars concentrate at a distance (5.1) well above both the  $B-V$  and the *Hipparcos* distance. This can be traced to the temperature scale for the two colors; the  $V-I$  colors for the cluster F stars imply temperatures significantly hotter than the  $B-V$  colors. The isochrones are brighter at the hotter temperatures, causing higher distance modulus estimates for these stars (smaller  $M_V$  implies larger  $m-M$ ). In Figure 17, we compare the temperatures from the isochrones in the two colors to those obtained by Boesgaard (1987) in a study of lithium in F stars. Boesgaard estimated temperatures from  $B-V$ , Stromgren photometry, and also measured spectroscopic temperatures; her temperature scale is in excellent agreement with the  $B-V$  temperature scale in the isochrones and in significant disagreement (at the 200–300 K level) with the  $V-I$  temperature scale for the F stars. Adopting the hotter temperature scale implied by the  $V-I$  colors would raise a series of problems: the lithium dip in Coma would be at hotter  $T_{\text{eff}}$  than for other clusters, it disagrees with spectroscopic temperature estimates and those from Stromgren photometry, and large internal variations in the derived iron abundances for cluster stars would result. We have no explanation for this problem, and reobserving the cluster stars in  $V-I$  and IR

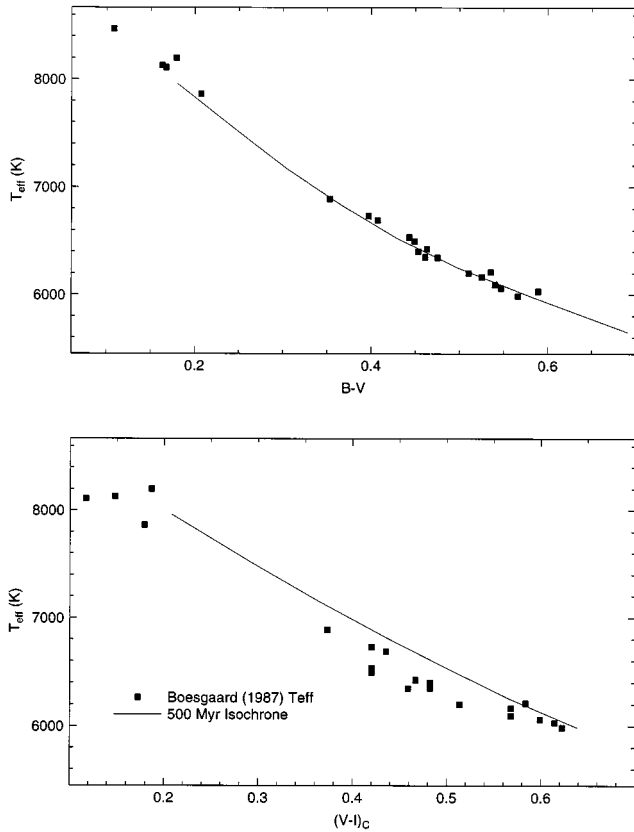


FIG. 17.—Effective temperatures for Coma Ber members from Boesgaard (1987) compared with those predicted from  $(B-V)$  (top) and  $(V-I)$  (bottom).

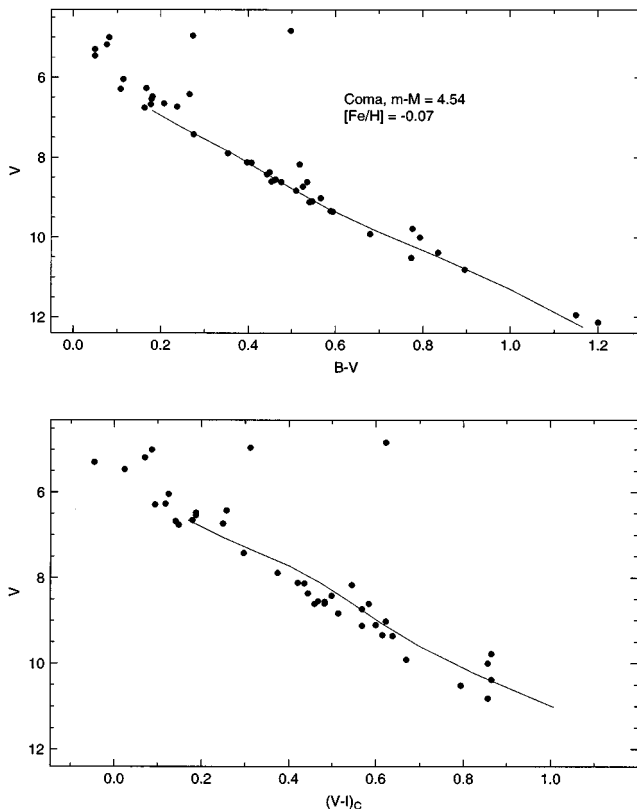


FIG. 18.—500 Myr theoretical isochrones (solid lines) with  $[\text{Fe}/\text{H}] = -0.07$  shifted to a distance of 4.54, compared with Coma Ber in  $(B-V)$  (top) and  $(V-I)$  (bottom).

colors would be useful to understanding it. We therefore do not use the  $V-I$  distance to the system, and our MS-fitting distance to this cluster must be taken with this discrepancy in mind. The cluster is compared to isochrones in both of our colors in Figure 18.

#### 4. DISCUSSION

The results of § 3 indicate that it is the *Hipparcos* distance to the Pleiades that conflicts most seriously with the MS fitting. In all the other systems except Coma Ber, MS fitting in different colors yields distance results that are consistent with one another, normal helium, and  $[\text{Fe}/\text{H}]$  values from high-resolution spectroscopy. Coma Ber may have an equally serious disagreement, but the unusual behavior of the cluster in  $V-I$  suggests that other problems may be contributing to the discrepancy. We therefore examine in turn the various possible mechanisms that could reconcile the cluster distance scales for the Pleiades; in all cases we believe that they cannot do so. In a companion paper we show that the same conclusions result from an examination of nearby field stars (Paper II). We then proceed to an analysis of the *Hipparcos* parallaxes for the Pleiades, and show that there are indications of possible systematic errors that could be the origin of the discrepancy.

The calculations we present are standard stellar models. We have therefore not included physical processes such as gravitational settling, rotational mixing, magnetic fields, internal gravity waves, or mass loss, which are surely present. There are strong reasons for believing that these nonstandard effects will not influence the distance scale, although they could be potentially important for other issues. The single most important reason is the youth of the clusters that we have examined; detailed nonstandard calculations predict little, if any, effect for ages as young as the Pleiades. In addition, any such process would have to affect stars with a wide range of masses to a similar extent and be different among different clusters to explain the pattern that we see.

Gravitational settling is minimal in young systems such as the Pleiades, and the degree to which helium and heavy elements sink depends strongly on the convection zone depth, and thus on the stellar mass. For example, helium and heavy-element diffusion are a 10% fractional effect in the Sun, which is almost 50 times older than the Pleiades. The observed cluster lithium abundances require a mild envelope mixing process, and models with rotational mixing that are consistent with the lithium data predict little or no deep mixing (Pinsonneault 1997). In addition, the observed range in rotation rates in clusters is large, and any extra mixing would produce a spread in MS properties rather than a uniform shift in the distance estimates. Other physical processes could affect the results, but they are still subject to a variety of observational constraints, which make a large effect unlikely.

We have compared different standard model calculations, and the zero-point offset is small (0.01–0.03 mag for stars between 5600 and 7000 K, for example). The systematic errors in the standard model distance estimates is therefore also too small to explain the results that we have obtained. We now discuss age, composition, and reddening effects.

##### 4.1. Age and Stellar Activity

It is well known that many young stars are heavily spotted; this could influence the color-temperature relation-

ship and therefore the distance estimates for young systems such as the Pleiades and  $\alpha$  Per. In Figures 1 and 2 we compared these two clusters at the *Hipparcos* distances in our two colors; the Pleiades is clearly anomalous with respect to  $\alpha$  Per if the *Hipparcos* distance scale is adopted. Since  $\alpha$  Per is younger and has a larger population of rapid rotators, if anything  $\alpha$  Per should be more anomalous than the Pleiades if our MS-fitting age estimates were in error because of activity. We note that similar conclusions can be obtained by comparing young and old field stars (Paper II). The narrow width of the Pleiades MS also indicates that a wide range in stellar activity does not produce a significant effect on the color-temperature relationship. For all these reasons, we reject the idea that youth is responsible for the difference between the distance estimates.

Another possibility is that activity could be influencing the Pleiades  $[\text{Fe}/\text{H}]$ , which has been derived from LTE model atmospheres. If such a phenomenon were at play, it might lead to derived abundances being a function of line strength due to the direct effect of activity on the stronger lines formed at smaller depths in the photosphere. We have a number of high-resolution spectra of Pleiades members that were originally obtained to study lithium abundances. We have analyzed the Fe I data in the cool Pleiades dwarfs and find no such  $[\text{Fe}/\text{H}]$ -line strength correlation. This does not exclude a real correlation, however, given the influence of damping, which is adjusted to enforce a lack of correlation. To the extent that our damping assumptions seem quite reasonable compared to numerous other fine spectroscopic analyses, and are consistently applied in both the stellar and solar analyses to yield line-by-line  $[\text{Fe}/\text{H}]$  values, the analysis suggests that any such trends are not substantial. In any case, any systematic error in the inferred mean  $[\text{Fe}/\text{H}]$  is greatly mitigated by the fact that the damping adjustments enforce consistency with the weaker lines, which are formed at deeper depths, and thus presumably are more immune to the direct effects of chromospheric activity. Activity in very young stars can manifest itself in the form of an effective veiling continuum. Such behavior would presumably weaken the line absorption, thus leading to *underestimated* line strengths and, hence, underestimated abundances. Detailed NLTE line formation calculations designed to determine how the active Pleiades dwarfs' Fe and other metal abundances might be affected by activity, spots, convective flows, etc. would be of interest, but are unlikely to produce large errors, for the reasons discussed above.

## 4.2. Heavy Metals

### 4.2.1. The Cluster $[\text{Fe}/\text{H}]$ Scale

Homogeneous Fe abundances are available for the Pleiades, Praesepe, and  $\alpha$  Per from the work of Boesgaard and collaborators. Independent modern fine analyses of these clusters (and a few others) by other investigators are available for comparison with their work. All the studies considered here derive self-consistent solar Fe abundances with which the stellar values are normalized. Such a careful differential procedure can greatly reduce errors introduced by varying assumptions concerning the solar Fe abundance, model atmospheres,  $gf$  values, etc.

Boesgaard et al. (1988) determine a mean Pleiades iron abundance of  $[\text{Fe}/\text{H}] = -0.03$  from an analysis of 17 F stars. The mean star-by-star reddening they use is essentially identical to the value we have adopted. Boesgaard

(1989) determined a "best" Pleiades abundance by analyzing new data for eight Pleiads; the result was  $[\text{Fe}/\text{H}] = +0.02$ . Boesgaard & Friel (1990) used new data for 12 of the same stars as in Boesgaard et al. to find a mean  $[\text{Fe}/\text{H}] = -0.03$ . The single-datum standard deviation in all these studies is  $\sim 0.07$  dex. The  $1\sigma$  level error in the mean is  $0.02$ – $0.03$  dex, so the internal statistical uncertainties appear to be small. Cayrel, Cayrel de Strobel, & Campbell (1988) derive a mean Pleiades  $[\text{Fe}/\text{H}]$  of  $+0.13$  from analysis of four Pleiades dwarfs, three of which are significantly cooler (mid G) than the Boesgaard F stars. The standard deviation is  $0.10$  dex, which is somewhat smaller than their estimated individual errors; the error in the mean is  $\sim 0.06$  dex. The  $\sim 0.1$  dex offset between the Cayrel and Boesgaard values is representative of uncertainties in reddening (which enters via photometric  $T_{\text{eff}}$  determinations by Boesgaard), the  $T_{\text{eff}}$  determinations (the Cayrel values are based on  $\text{H}\alpha$  profiles), and other details. The Cayrel result is consistent with Eggen's (1986) inference from narrowband photometry that the Pleiades  $[\text{Fe}/\text{H}]$  is near the Hyades value.

In order to increase the sample of Pleiades stars with  $[\text{Fe}/\text{H}]$  determinations, some of us (King et al. 1998) have used high-quality Keck spectra of two slowly rotating very cool ( $T_{\text{eff}} \sim 4500$  K) Pleiades dwarfs to derive Fe abundances. Our  $T_{\text{eff}}$  values are spectroscopic determinations from balancing the abundances as a function of excitation potential, and the normalized abundances are derived by comparison with similarly analyzed solar data on a line-by-line basis. The mean abundance is  $[\text{Fe}/\text{H}] = +0.06$ , with estimated errors in the mean of perhaps  $0.05$  dex. While comparison of the different studies indicates that there may be systematic errors at the  $0.1$  dex level, we regard this (dis)agreement to be quite satisfactory given the  $\sim 2000$  K range in  $T_{\text{eff}}$ , the disparate sources of the data, and the distinct methods used to derive  $T_{\text{eff}}$ . While a slightly subsolar Fe abundance is often assumed for the Pleiades based on the Boesgaard & Friel (1990) results, the totality of the high-resolution spectroscopic evidence may be more consistent with a slightly supersolar value; our photometric  $[\text{Fe}/\text{H}]$  is consistent with solar  $[\text{Fe}/\text{H}]$ . Therefore, if anything, the data suggest a distance modulus estimate larger rather than smaller than our MS-fitting value.

Fe abundances for Praesepe F dwarfs have been derived by Boesgaard et al. (1988), Boesgaard (1989), and Friel & Boesgaard (1992). The resulting values are  $+0.14$ ,  $+0.10$ , and  $+0.05$ , with star-to-star scatter of  $0.06$ – $0.07$  dex, and mean uncertainties of  $0.03$ – $0.04$  dex; again, the internal precision is good. The zero-reddening assumed in their  $T_{\text{eff}}$  determinations is identical to our assumption. Other detailed studies of numerous Praesepe stars for comparison are lacking. Analysis of the primary component of the Praesepe SB2 KW367, a mid-G star that is significantly cooler than the Boesgaard F stars, by King & Hiltgen (1996), yielded  $[\text{Fe}/\text{H}] = +0.01$ , with an uncertainty near  $0.05$  dex. Again, systematic errors at the  $0.1$  dex level are indicated by this limited comparison. Combined with the above results, we see that  $[\text{Fe}/\text{H}]$  for Praesepe is  $0.00$ – $0.15$  dex larger than for the Pleiades, with a preference for the lower middle of this range. The results inferred from MS fitting are consistent with the upper end of the range.

Boesgaard et al. (1988), Boesgaard (1989), and Boesgaard & Friel (1990) derived Fe abundances in  $\alpha$  Per F stars. The mean  $[\text{Fe}/\text{H}]$  values are  $-0.02$ ,  $+0.00$ , and  $-0.05$ . The  $\alpha$

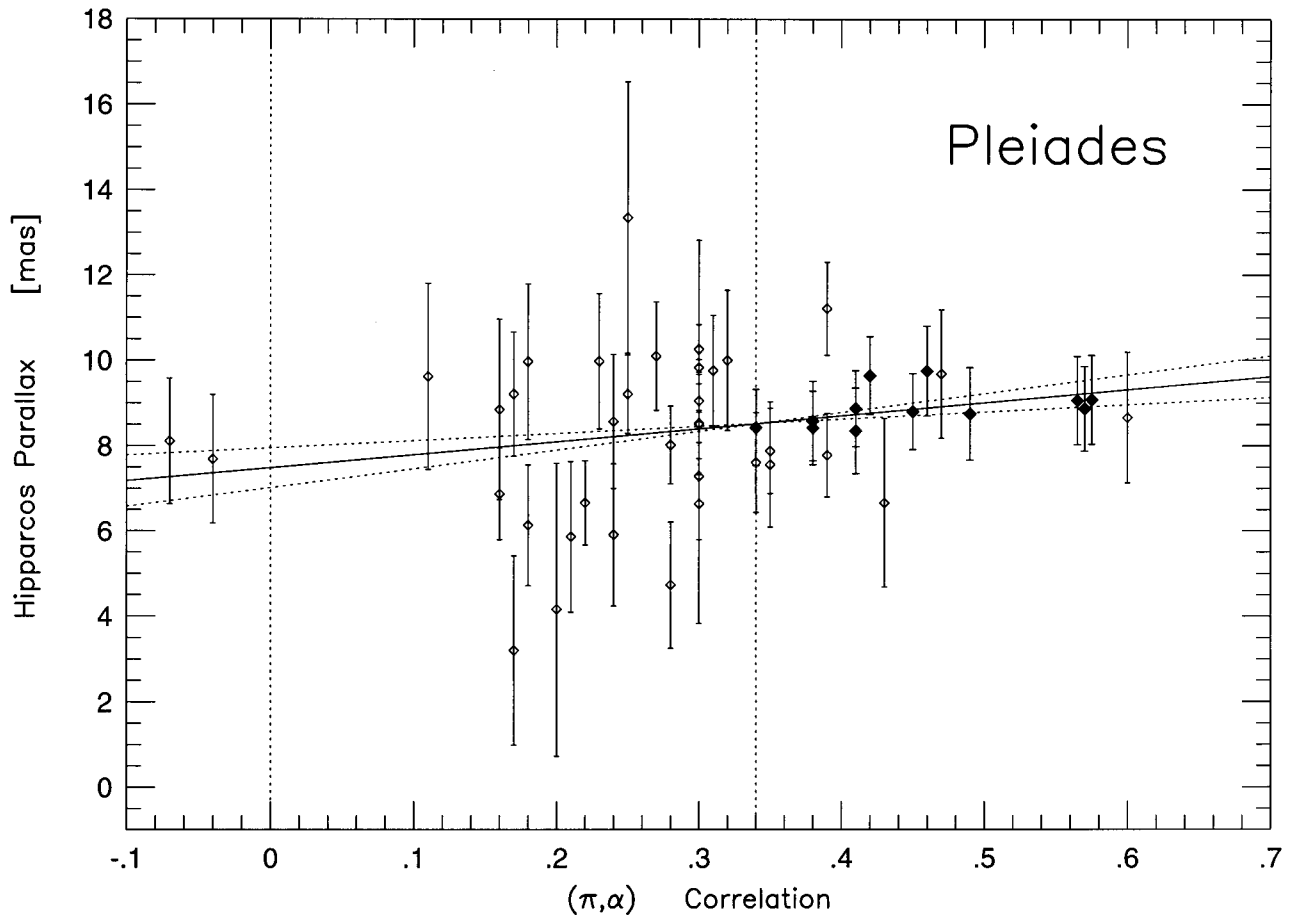


FIG. 19.—*Hipparcos* parallax vs. the correlation  $\rho_{\alpha}^{\pi}$  for 49 Pleiades members. Filled symbols show 12 bright ( $V < 7$ ) stars within  $\sim 1^{\circ}$  of the cluster center with correlations  $\rho_{\alpha}^{\pi} \geq +0.34$ . Vertical dotted lines mark  $\rho_{\alpha}^{\pi} = 0$  and the mean value  $+0.34$ . Sloping lines represent the weighted least-squares relation  $\pi = 8.53 + (3.04 \pm 1.36)(\rho_{\alpha}^{\pi} - 0.34)$  mas.

Per Fe abundance seems nearly identical to the Boesgaard Pleiades estimate. The star-to-star scatter in the larger  $\alpha$  Per samples is 0.08–0.09 dex; mean uncertainties are  $\sim 0.04$  dex. The mean of the individual  $\alpha$  Per reddening values employed by Boesgaard is  $\sim 0.03$  dex lower than the single value adopted here. This difference might require a 0.05–0.10 dex increase in  $[\text{Fe}/\text{H}]$  for consistency with our assumptions. Balachandran, Lambert, & Stauffer (1988) determined Fe abundances in a very wide range (types F to K) of  $\alpha$  Per stars. The mean abundance of the stars not considered by them to be nonmembers is  $[\text{Fe}/\text{H}] = +0.04$ , with a star-to-star scatter of 0.14 dex; the mean internal error is only 0.02 dex. Their assumed reddening is identical to our value. The results of Boesgaard et al. (1988) and Balachandran et al. (1988) agree to within 0.1 dex, but when adjustment is made for the slightly different reddening assumptions, the agreement is within a few hundredths of a dex if not exact. Our photometric  $[\text{Fe}/\text{H}]$  is slightly subsolar, at the 0.01–0.02 dex level. It thus appears that the Fe abundance of  $\alpha$  Per is not significantly larger than for the Pleiades.

In sum, internal errors in the Fe abundances of MS Pleiades, Praesepe, and  $\alpha$  Per stars derived from careful homogeneous analyses employing high-quality data lead to uncertainties of only 0.05–0.10 dex in relative cluster abundances. We have seen that systematic effects due to errors in reddening, differences in the analysis methodology, etc., may approach 0.15 dex. These are small compared to the

offset needed to explain the *Hipparcos*-based  $M_V$  values for the Pleiades. Barring fundamental failure or incompleteness in our understanding of spectral line formation and stellar atmospheres, the extant data suggests that the Fe abundances of the Pleiades, Praesepe, and  $\alpha$  Per are within  $\sim 0.10$  dex of each other. We might caution, however, that the abundances of other important atmospheric opacity contributors (e.g., Mg and Si) are, unfortunately, unknown.

#### 4.2.2. Photometric Constraints and the Binary Distance to the Pleiades

There are other factors that make a large error in the Pleiades  $[\text{Fe}/\text{H}]$  unlikely. Colors that incorporate an infrared band are less sensitive to metallicity than  $B-V$ . The figures in the previous section indicate clearly that the shift in the cluster distance modulus is the same for different color indices; the Pleiades must be intrinsically sub-luminous if the revised distance estimate is correct. The deviations from the high-resolution  $[\text{Fe}/\text{H}]$  values for the Pleiades are both large and inconsistent from color to color. The spectroscopic binary HD 23642 also provides a distance of  $5.61 \pm 0.26$ , consistent with MS fitting, albeit with a large error (Giannuzzi 1995).

#### 4.3. CNO Abundances

Carbon, nitrogen, and oxygen can affect stellar structure in ways other elements do not; are they anomalous in the Pleiades? As part of his thesis, King (1993) examined the

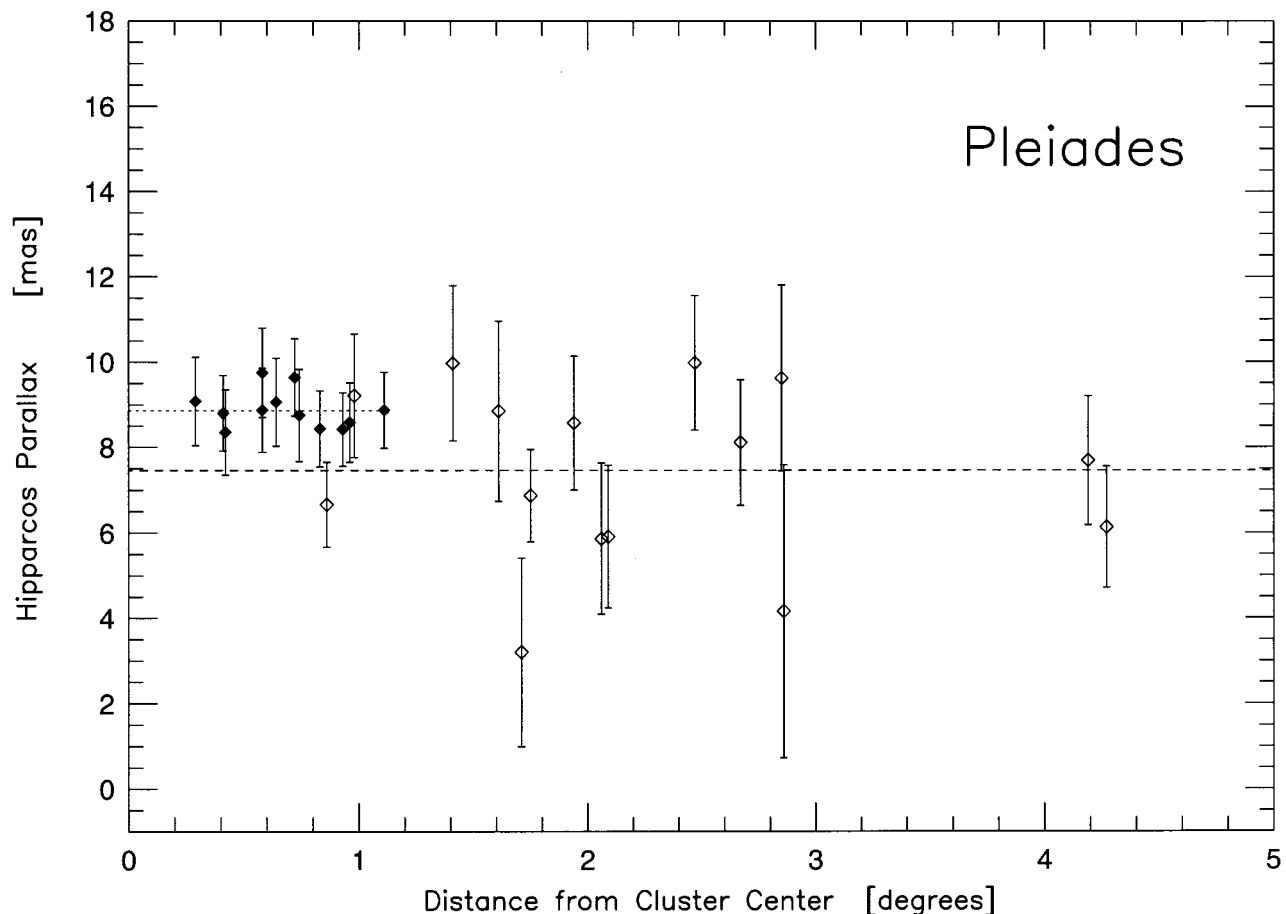


FIG. 20.—*Hipparcos* parallax vs. angular distance from the Pleiades cluster center. Filled symbols show the same 12 bright stars with high  $\rho_{\alpha}^2$  as in Fig. 14. Open symbols show the 15 stars with  $\rho_{\alpha}^2 < +0.25$ , with no restriction on magnitude or distance. The long-dashed line marks the mean parallax (7.46 mas) for these 15 stars. The dotted line marks the mean parallax (8.86 mas) for the 12 bright stars.

oxygen abundances of stars in several clusters over a broad range of age. The  $[O/H]$  for the Pleiades was found to be higher than for Praesepe (+0.29 and +0.02, respectively, with errors in the mean of 0.08 for both). However, the trustworthiness of abundances (such as these) derived from the high-excitation 7774 Å O I lines is a matter of some debate. In addition to possibly large data and analysis differences between various studies (e.g., King & Hiltgen 1996), there may be significant abundance corrections due to non-LTE effects on line formation in stellar atmospheres (see Garcia Lopez, Rebolo, & Perez de Taoro 1995). Unfortunately, systematic errors of 0.3 dex in the cluster O abundances derived from high-excitation lines remains plausible. In any case, the King results would act to make the Pleiades more metal rich and would therefore require a higher distance modulus estimate. Detailed abundance studies would be useful, but deviations from the solar mixture would need to be very large to have a significant impact on the luminosity of the MS.

#### 4.4. Helium

The initial solar helium abundance can be inferred from theoretical solar models by the requirement that the model have the solar luminosity at the age of the Sun. Modern evolution codes give estimates for the initial solar  $Y$  in the range of 0.26–0.28; the best solar models of Bahcall, Pinsonneault, & Wasserburg (1995) gave  $Y = 0.272$  and

$Y = 0.278$  with and without gravitational settling, respectively. A comparison of theoretical stellar models with the *Hipparcos* main sequence of the Hyades by Perryman et al. (1997) yields  $Y = 0.26 \pm 0.02$ ; for comparison, the solar  $Y$  in that study was 0.266 and the solar-scaled helium for the cluster would be 0.28. This agreement between the Sun and Hyades was anticipated and reinforces the notion that stars formed in the current epoch have similar helium abundances.

Nevertheless, we consider what range of  $Y$  would be needed to drop the Pleiades main sequence by 0.3 mag, and that value is about  $Y = 0.37$ . Such a high value of  $Y$  for the Pleiades would imply a drastic revision of chemical evolution models and, by extension, would raise the possibility that other clusters might have similar anomalies. MS fitting would therefore require knowledge of both the metal and helium abundances; since helium can only be directly observed in young systems, this would make MS fitting unreliable at the 0.3 mag level for the majority of clusters.

We believe that this question is best answered by direct measurements of the helium abundance in H II regions and massive stars. We begin with a discussion of the literature on helium abundances; we have also obtained data on the relative helium abundances in the Pleiades and  $\alpha$  Per. Neither the field-star data nor our Pleiades spectra are consistent with significant variations in the initial helium abundance from the solar value.



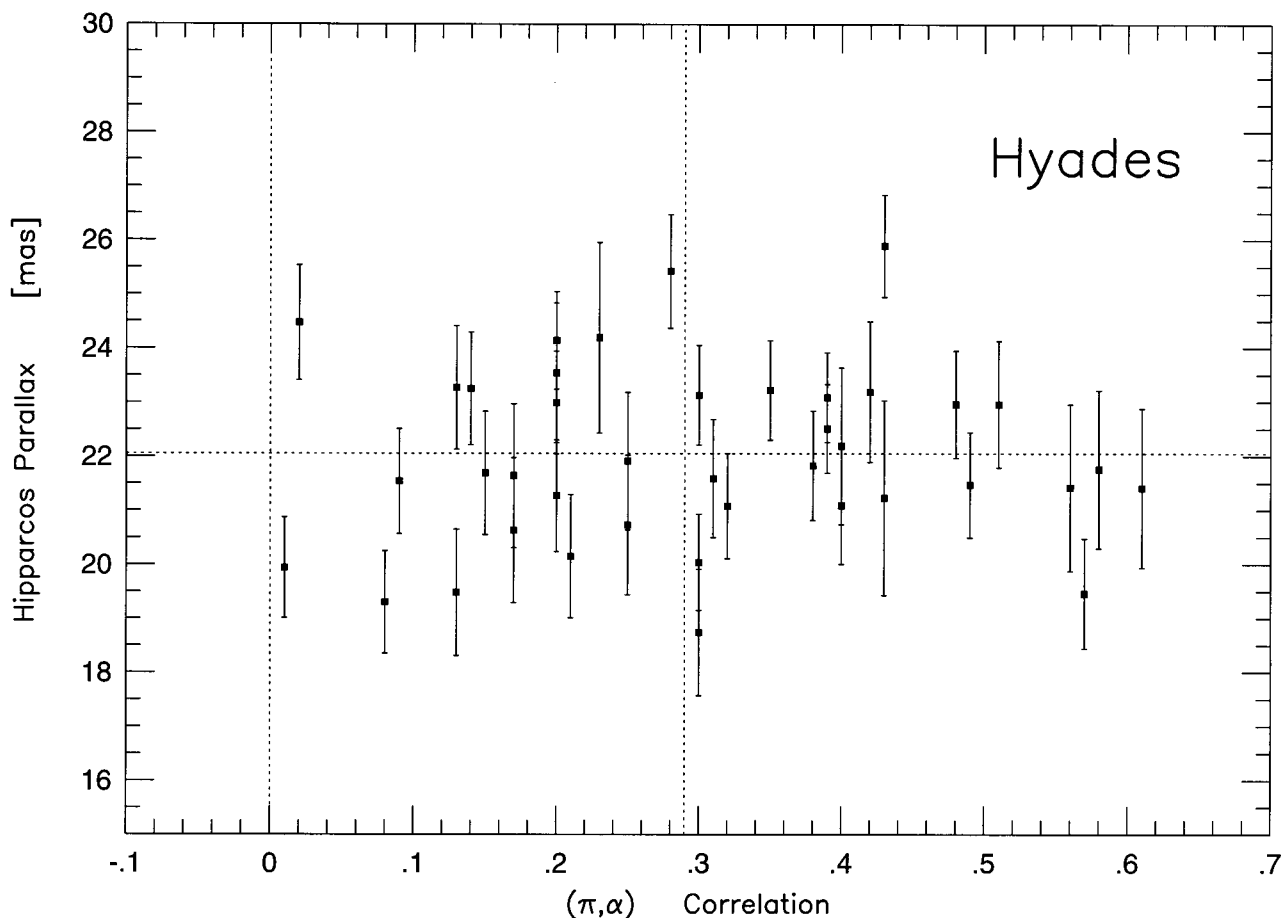


FIG. 21.—*Hipparcos* parallax vs. the correlation  $\rho_{\alpha}^{\pi}$  for the 40 Hyades cluster members listed in Table 8 of Perryman et al. (1997). Vertical dotted lines mark  $\rho_{\alpha}^{\pi} = 0$  and the mean value  $+0.29$ . Horizontal dotted line marks the mean parallax 22.05 mas.

Ignoring a deviant few percent of field stars, Nissen's (1974) study revealed no intrinsic scatter in  $Y$  greater than  $\sim 10\%$  (compared to the 30%–40% deviation required by the Pleiades stars) in nearby MS field B stars. Gies & Lambert (1992) found helium abundances consistent with both the Sun and the Orion nebula for a sample of 35 B dwarfs; four B supergiants in that sample were found to have anomalously high helium abundances. There is evidence that evolutionarily effects are responsible for helium enrichment in the most massive stars (for reviews, see Maeder & Conti 1994; Lyubimkov 1996; Pinsonneault 1997), so helium abundances from MS O stars and massive supergiants may not be reliable indicators of the initial  $Y$ . The B star field data and the Orion nebula abundances are therefore our best test for the range in helium abundance at solar metal abundance, and they are consistent with only small variations in the initial helium abundance.

For Galactic clusters, however, the picture is less clear. Shipman & Strom (1969), Peterson & Shipman (1973), Nissen (1976), and Lyubimkov (1977) found evidence for 20%–30% variations in  $Y$  among young associations, including some systems with significantly lower  $Y$ . Lyubimkov suggested an increasing He abundance with increasing age among the young clusters/associations studied, a conclusion not supported by the subsequent field-star work of Gies & Lambert (1992).

Patton (1979) determined He abundances of 60 stars in eight young clusters and associations. She noted that her

initial abundances displayed a range in  $Y$  of about 25%, and that this could not be explained by the usual error sources; she also called attention to a correspondence between He abundance and cluster age. However, Patton shows that binarity may be responsible for observed cluster-to-cluster He abundance dispersions and the notably low He abundances (also observed by others) seen for a few stars within a given cluster or association. Eliminating suspected (but not positively identified) binary systems from her analysis results in cluster He abundances that are identical to within the uncertainties. This highlights the need for secure knowledge of very fundamental stellar parameters (e.g., binarity) before reliable He abundances can be derived.

With this muddled picture of MS stellar He abundances, one may wonder whether the Pleiades He abundance could be abnormal. Both the Pleiades and  $\alpha$  Per are young enough to have B stars, and their helium can be directly measured. The  $Y$  values from Lyubimkov (1977) agree to within  $\Delta Y \sim 0.015$ , which is well within the uncertainties; the Pleiades and  $\alpha$  Per  $Y$  value is 0.04 larger than the corresponding field-star value, but the uncertainties are comparable to this offset. Klochkova & Panchuk (1986) also derived B star He abundances in both the Pleiades and  $\alpha$  Per. They claim to find no difference between the mean abundances larger than the uncertainties. However, this conclusion is not clear to us from the abundances listed in their Table II, which do demonstrate quite large differences. Unfortunately, only two Pleiades stars are included in the

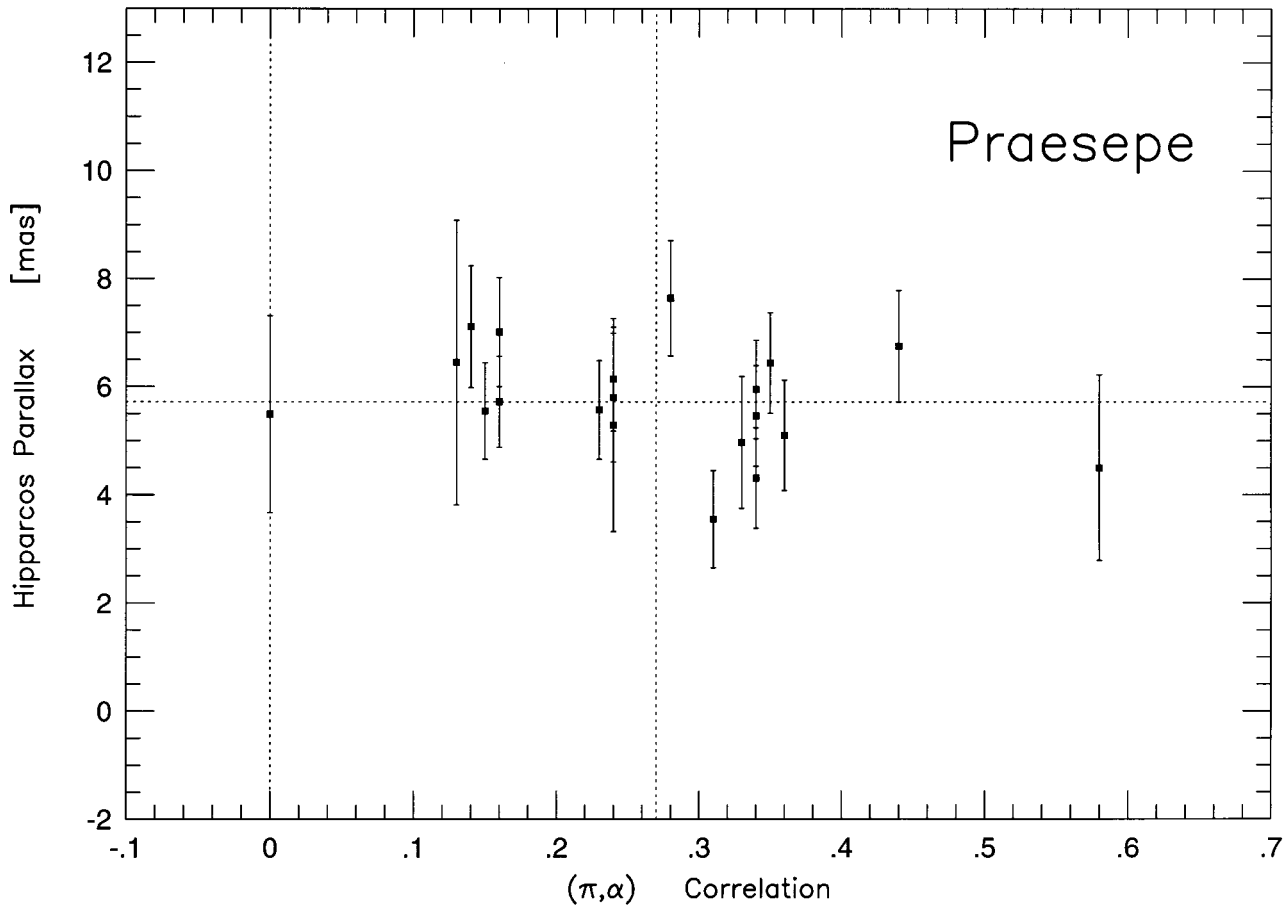


FIG. 22.—*Hipparcos* parallax vs. the correlation  $\rho_{\alpha}^{\pi}$  for 20 Praesepe cluster members, verified by proper motion and position in the color-magnitude diagram. Vertical dotted lines mark  $\rho_{\alpha}^{\pi} = 0$  and the mean value  $+0.27$ . Horizontal dotted line marks the mean parallax 5.72 mas.

analysis. Therefore, small number statistics and the possible effects of binarity make assessment of this difference difficult. We attempted a final comparison using the “field” stars from Nissen (1974). This sample includes four  $\alpha$  Per stars and two stars (HR 5191 and 7121) that are suggested members of the purported Pleiades supercluster. The mean  $Y$  value is only 0.03 larger for the Pleiades field stars than for the  $\alpha$  Per stars; the uncertainties are probably not much smaller than this difference.

To investigate the possibility of a nonstandard helium abundance in the Pleiades, Fischer & King (1998) observed MS B stars in  $\alpha$  Per and Pleiades to differentially compare the helium abundances. Preliminary analysis of the lines strengths for six He lines suggests that the cluster He abundances are identical to within an uncertainty of 15%. Any real difference appears to be in the opposite sense of what is needed to make the Pleiades underluminous: the Pleiades line strengths are, if anything, consistently smaller than the  $\alpha$  Per counterparts.

#### 4.5. Reddening and Systematic Errors in the Photometry

Reddening will tend to make a cluster MS fainter at a given color. If the reddening is increased, the inferred distance modulus will also increase. The effect can be roughly estimated as follows. In the color interval we use for MS fitting, the derivative of  $M_V$  with respect to both  $B-V$  and  $V-I$  is  $\sim 5$ . The extinction is  $A_V = 3.12E(B-V)$  and  $E(V-I)_K = 1.5E(B-V)$ . Adding these effects, an increase in

$E(B-V)$  of 0.10 mag would increase  $V$  at fixed  $B-V$  and fixed  $V-I$  by 0.188 mag (0.5 mag from a shift of 0.1 in  $B-V$ , 0.312 mag from extinction) and 0.438 mag (0.75 mag from a shift of 0.15 in  $V-I$ , 0.312 mag from extinction), respectively. The relative distances inferred from the two colors could therefore be affected if the reddening is incorrect. In addition, the  $[\text{Fe}/\text{H}]$  abundances derived for cluster stars are sensitive to  $T_{\text{eff}}$ , and an increased reddening would imply a higher  $[\text{Fe}/\text{H}]$  for a given equivalent width (therefore further increasing the distance modulus). Other colors, such as  $R-I$ , will be less reddening sensitive.

Neither the Hyades nor Praesepe show any evidence for reddening along the line of sight; increasing the reddening estimate for the Pleiades would worsen the discrepancy with the *Hipparcos* distance modulus estimate. Even changing  $E(B-V)$  from 0.04 to 0 would only decrease the distance modulus by 0.08 mag. The reddening estimates for the Pleiades have been derived for a wide range of masses and using different techniques; Crawford & Barnes (1974) used Stromgren photometry to estimate  $A_V$  for B, A, and early F stars in the Pleiades and Praesepe; both Prosser and Stauffer used M dwarfs in the same clusters; and Breger (1986) used polarization measurements in the Pleiades. We conclude that reddening is not a significant source of uncertainty in distance estimates for the Pleiades. Multicolor distance measurements of the type performed in this paper could be a useful check on the reddening for more heavily obscured systems.

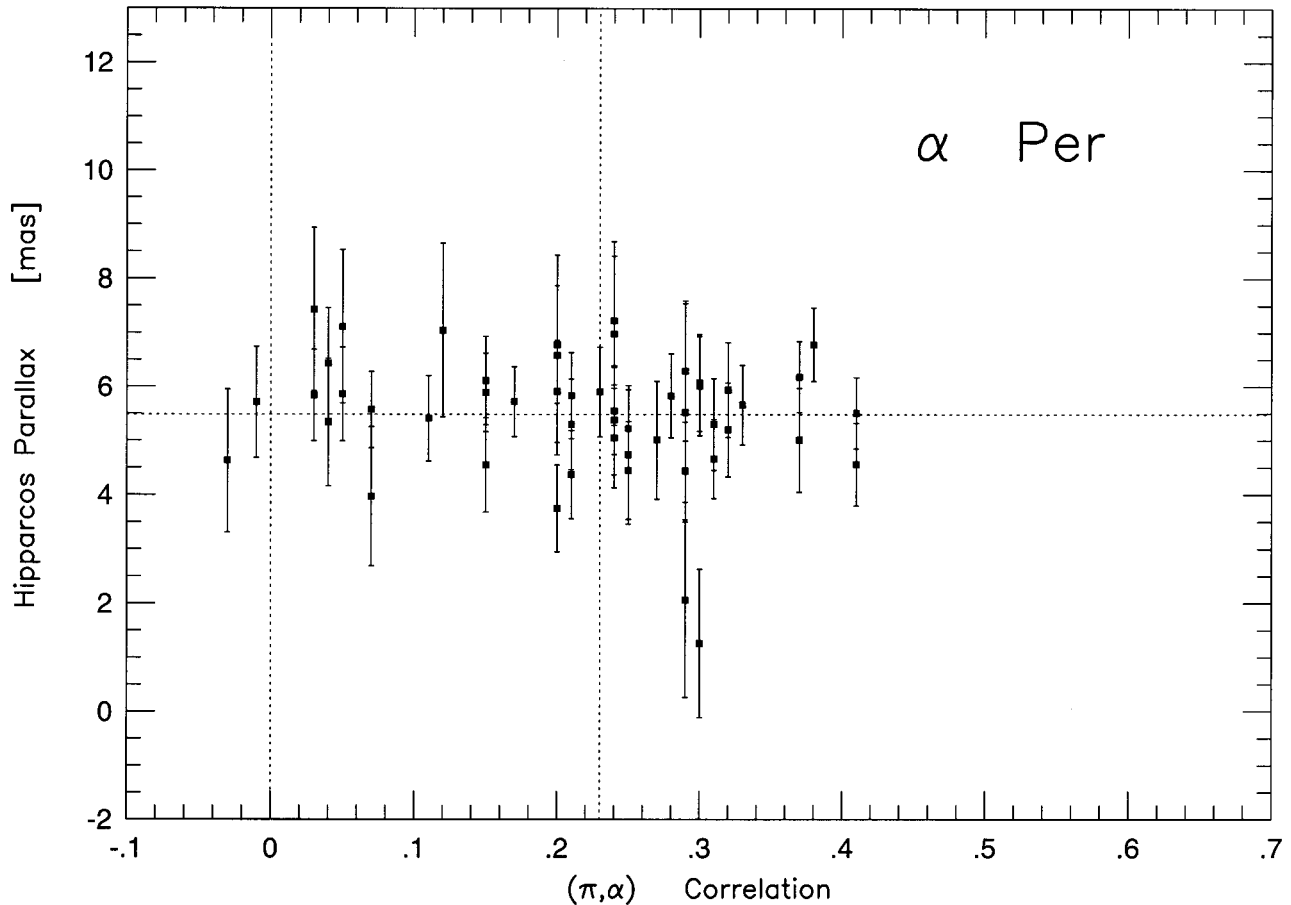


FIG. 23.—*Hipparcos* parallax vs. the correlation  $\rho_{\alpha}^{\pi}$  for 51  $\alpha$  Per cluster members, verified by proper motion, radial velocity, and position in the color-magnitude diagram. Vertical dotted lines mark  $\rho_{\alpha}^{\pi} = 0$  and the mean value  $+0.23$ . Horizontal dotted line marks the mean parallax 5.48 mas.

Another possibility is that systematic errors in the photometry could cause errors in the distance estimates. For the color range we are considering, the slope of the MS is  $\sim 5$ ; this would require a systematic error of 0.06 mag in  $B-V$  to reconcile the Pleiades distance scales, which is unreasonably large. The size of the systematic errors can be constrained by comparing spectroscopic temperature estimates with those based on colors. In the case of Coma Ber, for example, it appears that spectroscopic temperature estimates are in agreement with the  $B-V$  colors of F stars but not with their  $V-I$  colors. We note that the slope of the MS in  $V-I$  is steeper for F stars than for the cooler stars, and that systematic errors in the  $V-I$  photometry might explain the puzzling behavior of Coma Ber. We have attempted whenever possible to rely on a single source for photometry in a given color for a given cluster. Even in the case of the  $V-I$  data, we see no evidence of systematic differences between the location on the color-magnitude diagram of stars with colors converted to the Cousins system from the Kron system and those converted to the Cousins system from the Johnson system.

For the Pleiades, independent studies (§ 2.2) give consistent photometry for individual stars at the level of the quoted errors (0.01–0.02 mag). The 0.3 mag discrepancy between the *Hipparcos* and MS-fitting distance moduli is much too large to be explained by systematic errors in the photometry. High-resolution spectroscopy of the Pleiades is consistent with the observed colors, and the reddening is

small. For systems with higher reddening, however, care must be taken when converting between different photometric systems; the Johnson, Cousins, and Kron system  $I$  bands have different effective central wavelengths and therefore different reddening corrections.

#### 4.6. Systematic Errors in the *Hipparcos* Parallaxes

The final possibility is that the *Hipparcos* Pleiades parallaxes may contain previously undetected systematic errors. If the MS-fitting result  $m-M = 5.60$  does indeed give the correct Pleiades distance, then a systematic zero-point error would need to approach the 1 mas level in order to produce the discordance with the *Hipparcos* results. Such an error seems impossibly large, in view of the extensive tests of Arenou et al. (1995, 1997), who demonstrated the global zero-point error of the *Hipparcos* parallaxes to be smaller than 0.1 mas. However, global tests have little power to reveal effects occurring on the small angular scale ( $\sim 1^\circ$ ) of the *Hipparcos* spatial correlations (see below). Indeed, the *Hipparcos* parallaxes of stars in open clusters such as the Pleiades represent the first real opportunity to test for systematic effects on small angular scales. One might well argue that it would only be prudent to consider the *Hipparcos* cluster results as the first direct tests for small-scale zero-point errors, rather than as cluster distance measurements.

The *Hipparcos* Pleiades parallax (van Leeuwen & Hansen Ruiz 1997a) is based on measurements of 54 cluster

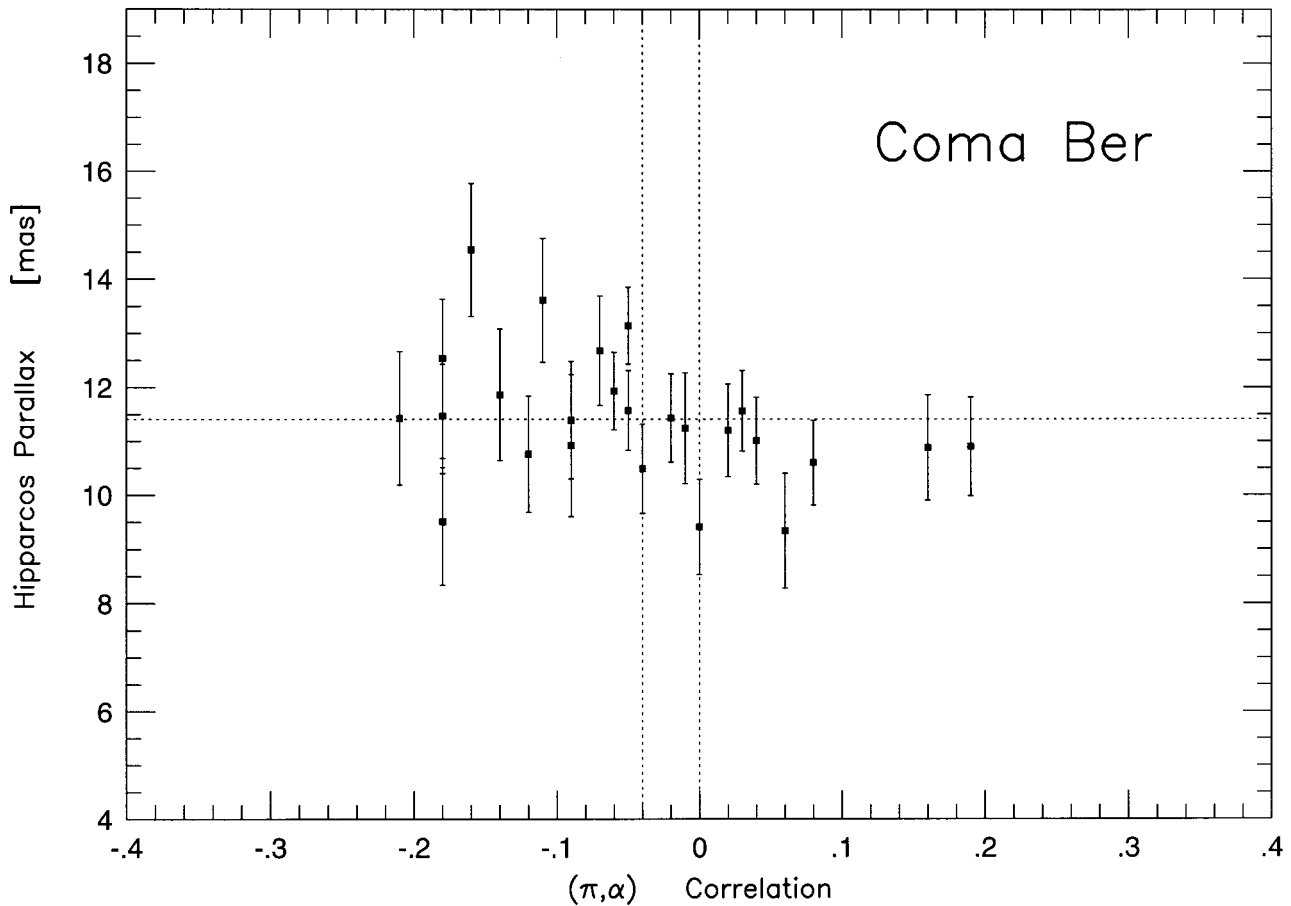


FIG. 24.—*Hipparcos* parallax vs. the correlation  $\rho_{\alpha}^{\pi}$  for 26 Coma Ber cluster members, verified by proper motion and position in the color-magnitude diagram. Vertical dotted lines mark  $\rho_{\alpha}^{\pi} = 0$  and the mean value  $-0.04$ . Horizontal dotted line marks the mean parallax 11.41 mas.

members, ranging in  $V$  from 2.8 to 11.5, within  $5^{\circ}$  of the cluster center, so it represents a fairly broad sampling of the cluster. Because *Hipparcos* observed widely separated ( $\sim 58^{\circ}$  apart) star fields simultaneously, the parallaxes are inherently on an absolute scale over the whole sky. Over small regions of the sky ( $\lesssim 2^{\circ}$ ), however, the astrometric results are positively correlated, because neighboring stars (within the  $0.9 \times 0.9$  *Hipparcos* field of view) tended to be observed on the same great circles that the satellite swept out over the sky (Lindgren 1988, 1989). A comprehensive discussion of the *Hipparcos* mission and data reductions is given in Volumes 1–3 of the *Hipparcos* Catalogue (European Space Agency 1997). The spatial correlations may significantly impact the astrometric results for star clusters, whose angular size is of the same order as the *Hipparcos* correlation scale. To account for this, van Leeuwen & Hansen Ruiz (1997a) recalculated the Pleiades mean parallax from the intermediate *Hipparcos* data. For this paper, one of us (R. B. H.) has reexamined the individual Pleiades parallaxes from the *Hipparcos* Catalogue.

Moreover, in addition to the spatial correlations, there is a different type of correlation affecting the *Hipparcos* results—the statistical correlations among the five astrometric parameters (position, proper motion, and parallax), arising from the imperfect distribution of *Hipparcos* observations on the sky over time.

In classical parallax work (cf. Vasilevskis 1975), the time distribution of observations over a star's parallactic ellipse is controlled to maximize the parallax factors and minimize

the correlations between position, proper motion, and parallax. This is easy to achieve from the ground, but *Hipparcos* could not do this because of the limited span of observations and the pattern of scans of the sky, as explained in § 3.2.4 of the *Hipparcos* Introduction (European Space Agency 1997, Vol. 1, pp. 321–325). Figures 3.2.42 to 3.2.61 of that work illustrate the patterns of the correlations over the sky; Figure 3.2.66 (p. 363) shows histograms of the 10 correlations. The rms values are  $\sim 0.2$ , and large areas of the sky show correlations averaging 0.4 or more in size. It must be emphasized that these correlations are substantially larger than would be considered acceptable in ground-based parallax observations.

For parallax work, the most important correlation is  $\rho_{\alpha}^{\pi}$ , between parallax and right ascension (Field H20 in the *Hipparcos* Catalogue). This is because over most of the sky, most of the extent of the parallactic ellipse is in right ascension. The *Hipparcos*  $\rho_{\alpha}^{\pi}$  correlation is shown in Figure 3.2.44 of the *Hipparcos* Introduction. Large values of  $\rho_{\alpha}^{\pi}$  were caused in certain areas of the sky by the unfortunate circumstance of unequal observations on either side of the Sun, as discussed in the *Hipparcos* Introduction (European Space Agency 1997, p. 325).

This happens to impact the Pleiades particularly badly. The mean value of  $\rho_{\alpha}^{\pi}$  near the Pleiades center is  $+0.4$ ; this is at the 96th percentile in the histogram in Figure 3.2.66. The question this raises is whether this large correlation, caused by the time distribution of *Hipparcos* observations of the Pleiades stars, has any effect on the parallax values.

We stress again that this is a different effect from the spatial correlation that exists because *Hipparcos* astrometric data over small ( $\sim 1^\circ$ ) areas of the sky are not fully independent measurements.

In Figure 19, we plot parallax versus the correlation  $\rho_\alpha^\pi$  for 49 Pleiades members verified by proper motion, radial velocity, and position in the color-magnitude diagram. (The 51 stars of Mermilliod et al. 1992 and the 54 of van Leeuwen & Hansen Ruiz 1997a are virtually the same set as these; we rejected several additional stars because of problems noted in Fields H30 and H59 of the *Hipparcos* Catalogue.) This plot shows several interesting things.

The filled symbols show 12 bright ( $V < 7$ ) stars within  $\sim 1^\circ$  of the cluster center with correlations  $\rho_\alpha^\pi \geq +0.34$  (the mean value for the whole sample). Because of the spatial correlation effect, these 12 stars all have nearly the same parallax (mean 8.86 mas, rms dispersion 0.45 mas;  $\chi^2$  too small at the 0.995 significance level). Because the *Hipparcos* errors are smallest for bright stars, these stars carry much of the weight of the Pleiades parallax.

There is a clear trend (slope) of parallax versus  $\rho_\alpha^\pi$  correlation; a weighted least-squares solution gives a slope of  $+3.04 \pm 1.36$  mas per unit correlation. The solid line in Figure 19 shows this slope, run through the mean point ( $+0.34, +8.53$ ). The dashed lines show  $\pm 1 \sigma$  slopes. The intercept at zero correlation is  $\pi = 7.49 \pm 0.50$  mas, quite consistent with the MS-fitting distance.

Figure 20 plots parallax versus distance from the cluster center. The filled symbols show the same 12 bright stars with high  $\rho_\alpha^\pi$  as in Figure 16. The open symbols show the 15 stars with  $\rho_\alpha^\pi < +0.25$ , with no restriction on magnitude or distance. The two sets of stars barely overlap because the brightest stars in the Pleiades are highly concentrated to the cluster center. The low-correlation stars lie farther from the Pleiades center and show a much larger parallax scatter, reflecting (1) the larger errors for fainter stars and (2) the lack of spatial correlations on scales  $\gtrsim 1^\circ$ . Moreover, their mean parallax is smaller (reflecting the slope discussed above). For the 15 stars with  $\rho_\alpha^\pi < +0.25$ , the weighted mean parallax is  $7.46 \pm 0.43$  mas. The rms dispersion is 1.66 mas, consistent with the published parallax errors.

This exercise is not intended to be a definitive redetermination of the Pleiades parallax; that would require going back to the intermediate *Hipparcos* data as per van Leeuwen & Hansen Ruiz (1997a, 1997b) and exploring the effects of both the  $\rho_\alpha^\pi$  and the spatial correlations at that level. However, it is quite clear that (1) small angular scale systematic effects at the 1 mas level are present in the *Hipparcos* Pleiades parallaxes; (2) these effects are related to the high values of the  $\rho_\alpha^\pi$  correlation near the cluster center; (3) the bright stars within  $\sim 1^\circ$  of the center, which carry most of the weight of the mean parallax, are the most severely affected; and (4) the stars with lower  $\rho_\alpha^\pi$  correlations, far enough ( $\gtrsim 1^\circ$ ) from the center to be unaffected by the spatial correlation, have smaller parallaxes, consistent with the MS-fitting distance.

We also looked for effects of the  $\rho_\alpha^\pi$  correlation in the Hyades, Praesepe,  $\alpha$  Per, and Coma Ber clusters. In Figures 21–24, we present the parallax versus correlation plots for those clusters. The Hyades, Praesepe, and  $\alpha$  Per clusters also have large values of  $\rho_\alpha^\pi$ , but the slope ( $d\pi/d\rho$ ) present in the Pleiades data does not occur in these clusters, in which the MS-fitting distances and the *Hipparcos* distances are in good agreement. The data for Coma Ber do show a slope of

$d\pi/d\rho = -4.0 \pm 2.1$  mas, but the range of  $\rho_\alpha^\pi$  is small, and the mean is near zero.

## 5. RESOLUTION OF THE PROBLEM

The *Hipparcos* distances to the open clusters can be regarded as either a test of the theory of stellar structure and evolution or as a test of the parallaxes themselves. To distinguish between the two, it is necessary to determine the errors in stellar interior-based cluster distances. We have performed a detailed multicolor analysis of the distances to the nearby open clusters, and verify that MS fitting can be performed to a precision of order 0.05 mag. With the exception of Coma Ber, distance estimates from  $B-V$  and  $V-I$  colors can be used to get photometric  $[\text{Fe}/\text{H}]$  values accurate at the 0.05 dex level, and these estimates are in good agreement with those obtained from high-resolution spectroscopy. There is a small zero-point shift, on the order of 0.04 dex, between our photometric abundance scale and that of Friel & Boesgaard (1992); if we adopted our zero-point, the distance estimates we have reported would all be increased by 0.04 mag. We also note that the distances inferred for rapid rotators are not consistent for the two colors; this implies that color temperatures for these stars may be in error, especially if they are derived from  $B-V$  colors. This may play some role in the lithium-rotation correlation seen in young rapidly rotating stars.

We have shown that the internal consistency of MS fitting is high, and in the particular case of the open clusters, the systematic errors are small. The basic cluster data (abundances, reddening, etc.) are also well established for the systems that we have studied in this paper. The extremely good agreement between helioseismology and theoretical solar models places strong constraints on missing physics in the models, and by extension the properties of solar analogs should be accurately represented by the models. For all these reasons, we believe that the open cluster distance scale from MS fitting is on very strong ground.

The *Hipparcos* mission permits a comparison of parallax and MS-fitting distances for a number of open clusters. In two of the systems that we have studied ( $\alpha$  Per and the Hyades), the two distance scales are in very good agreement. In Coma and the Pleiades, they disagree at the 0.2 and 0.3 mag level, respectively; these differences are at the 3.4 and 3.7  $\sigma$  level, respectively. The different distance scales for Praesepe are either very close (0.08 mag) or discrepant (0.33 mag), depending on which of the *Hipparcos* distance measurements is adopted; the latter would be a 2  $\sigma$  disagreement. We have searched for sources of error in the MS-fitting distances of Coma Ber and the Pleiades. The  $V-I$  photometry of Coma yields a distance that disagrees with both *Hipparcos* and  $B-V$ ; this can be traced to a discrepancy in the temperature scales for the two colors in this cluster. Although we believe that there are a number of indications that the  $B-V$  temperature scale is correct (consistency with spectroscopic temperatures and Stromgren photometry, for example), reobserving this cluster in IR and near-IR colors would be highly desirable to quantify the magnitude of the problem.

In the case of the Pleiades, there is no such ambiguity; different colors yield identical distances. Errors in the metal abundance and reddening as a solution can be rejected on a variety of grounds. The increase in the cluster helium abundance needed to reconcile the distance estimates is large and

not consistent with direct measurements. Furthermore, we can find no counterparts to the Pleiades in the field, i.e., intrinsically faint, solar-abundance stars (Paper II). We are therefore left with the uncomfortable choices of either requiring unknown physics in the interior models or recognizing a problem with the *Hipparcos* parallax distance scale to the Pleiades. The former choice is made even less attractive by the requirement that the models retain agreement with the Sun, the other clusters, and numerous other tests of the theory of stellar structure and evolution. We therefore believe that the latter explanation is more likely.

We have shown that there is evidence in the Pleiades data for systematic errors in the parallaxes on small angular scales. The same trends are not present in the clusters where the two distance scales agree; they may also be present in the Coma Ber cluster. Clusters such as the Pleiades provide many more stars within a small region of the sky than are present for the sky as a whole, and they are therefore uniquely suited to test systematic effects at small angular scales. The other clusters and the Pleiades show no evidence for systematic errors on scales larger than  $1^\circ$ . The Pleiades

results suggest that individual parallax measurements with large  $\rho_z^2$  correlations should be treated with caution. The implications of this result for other applications of the *Hipparcos* parallaxes will depend on the characteristics of the sample. For large samples over large regions of the sky, the net effect will be a modest increase in the overall error. As a numerical example, Arenou et al. (1997, pp. 441–443) find the overall ratio of *Hipparcos* “external” to “internal” errors to be  $1.06 \pm 0.07$  from clusters and  $1.04 \pm 0.04$  from distant stars. With the internal error  $\sim 1$  mas, this is equivalent to an additional (in quadrature) error of  $\sim 0.2$ – $0.4$  mas. This may in fact be the rms size of the small-scale errors.

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